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REVIEW OF LIGHTNING PROTECTION TECHNOLOGY FOR TALL STRUCTURES

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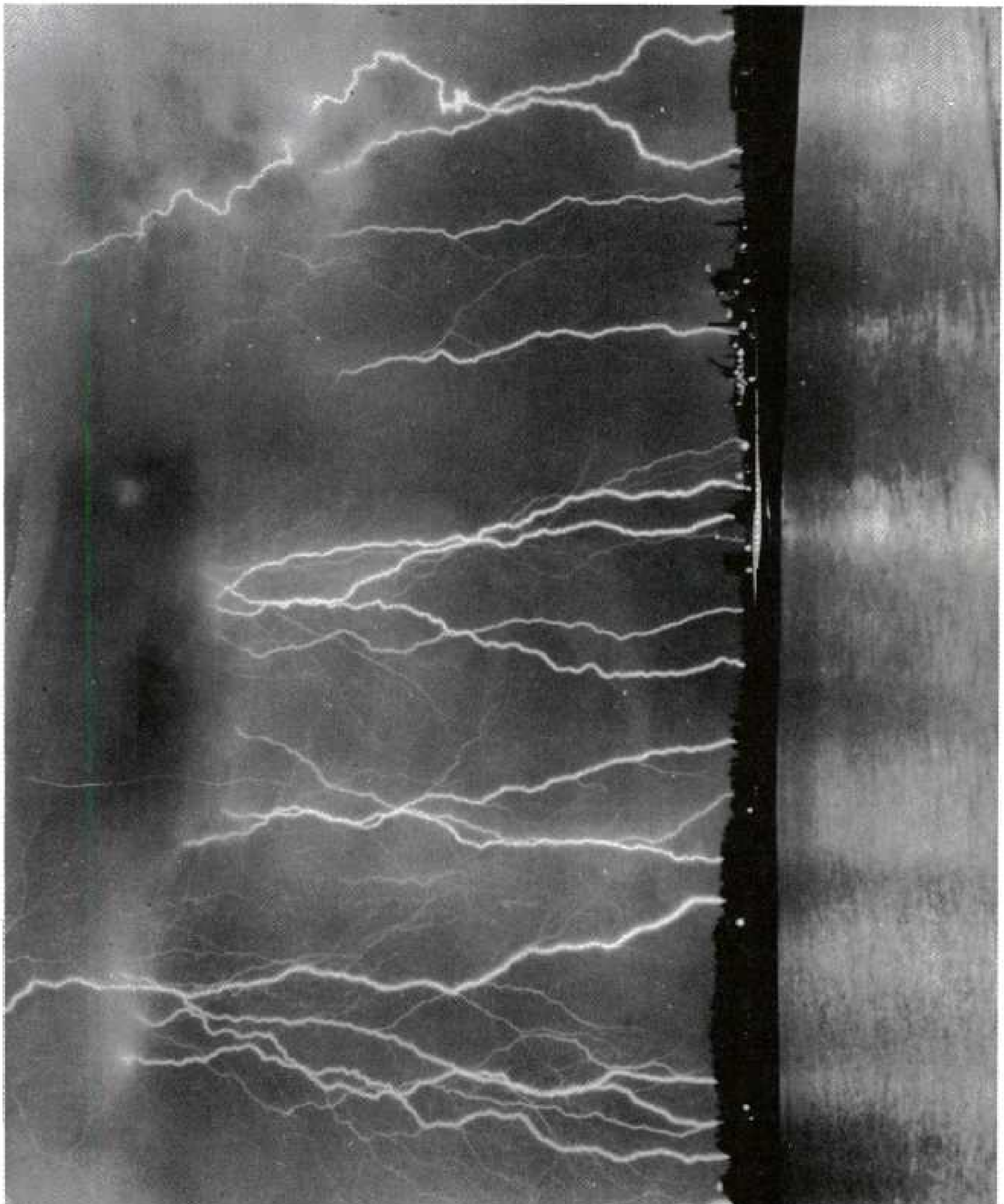
November 6, 1975

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH

ONR



CONTENTS

INTRODUCTION

The collection of papers and reported discussions in this volume represent an attempt to make some evaluation of the ability of corona-point arrays to absorb, suppress, eliminate, or in some way, protect against direct strike of lightning to surface structures. Those impaneled for the review and discussion are from among the best informed investigators of lightning phenomena in this country. In addition, the volume contains two invited papers by specialists from Great Britain.

The discussions center mainly, though not exclusively, around the operation of a commercial product marketed by Lightning Elimination Associates (LEA). The LEA product, a corona-point array, is intended to protect a structure and the area around it from lightning strike, by in some way suppressing the stroke, as distinguished from the operation of the lightning rod, which protects by conducting the lightning through a predetermined, low-resistant path to the ground.

The idea of using corona discharge to protect surface structures has a long history. It stems at least from the time of Franklin, who considered the idea, but quickly abandoned it in favor of the pointed lightning rod. In 1930, the idea was the subject of a patent issued to J. M. Cage of Los Angeles, who applied it in the form of point-bearing wires suspended from a steel tower to shield petroleum storage tanks against lightning. The latest proponent and vendor known to us of such a device is LEA.

Although this review has not settled in any final way what, if any, is the effect of corona-point discharge on lightning propagation or direction of movement, or what the optimum technology of protection is, it has, nevertheless, illuminated certain other questions and particularly that of the efficacy of blunt or pointed rods for lightning protection. Professor Charles Moore, for example, and his graduate student, Ron Standler, made both experimental and numerical studies of corona discharge and electrical field breakdown from rods with both blunt and pointed geometries. His findings were that when local breakdown field values were exceeded, ions from the smaller radius rod were emitted and quickly transported as by streamer to a distance where the radial field was no longer sufficient to support streamer propagation. Professor Moore's conclusions are that his numerical modelling supports experimental results that show a smaller radius rod to be self-protective by the ease with which it goes into corona emission, whereas the blunt geometry withholds its corona emission until a very much larger field value is exceeded. It is then exposed to a catastrophic field breakdown, in which there is streamer propagation to a much greater radial distance. Thus, where both exist, it is the blunt object, rather than the sharp one, that is likely to supply the junction streamer to an approaching lightning stepped leader. Professor Moore therefore suggests that some combination of blunt and pointed rods would improve lightning rod systems, with the blunt rod providing the stroke's preferred entrance to earth. He cautions, though, that this is no guarantee that the pointed rod cannot be hit, depending on the rate of rise of the field.

Sigrid Llewellyn's mathematical analysis of the performance of narrow and broad structure geometries, in general, support Professor Moore's analysis and, in addition, furnish additional insights into lightning strike phenomena. For example, one can see, from Figure 1 of her paper, an explanation of why a narrow geometry structure can be struck at a position below the top of the structure. The tightness of the potential gradient of the field extends for a considerable distance down and close to the side of the structure, making breakdown possible at many locations other than the top. From the same figure, one sees that a strong potential gradient extends to a greater distance from a blunt structure, so that field lines from a greater horizontal distance from the vertical extension of the structure can find their way to the base of the structure. Such information provides useful handbook data as to how to space lightning-attractive structures for the protection of an area.

Interestingly enough, from her analysis of the performance of a point above a blunt structure, Miss Llewellyn provides a clue as to how a corona-point array could suppress at least upward-going leaders, if the array had a special and critical design. The design would have to allow approach to the theoretical ideal that would permit such uniform and low corona discharge from all the points of the array that the transition of the resulting glow condition to an arc condition from any point would be inhibited, thus discouraging initiation of an upward-going leader. Dr. Golde, in his paper, also explains this technique. None of the arrays under discussion here begin to approach such formidable design criteria and apparently, in the long history of attempts to apply corona discharge to suppression of lightning, there is no awareness that such an ideal design might accomplish the task.

For prevention of lightning strokes by another technique Dr. Golde reminds us of the electrode shields used in ultra high voltage laboratories over various pieces of equipment to prevent flash over. Conceptually, if not practically, a similar electrode shield could be used to cap a tall tower or mast for lightning protection.

The various analyses further show that, as far as lightning prevention is concerned, corona discharge is a forlorn hope as an explanation for taking the sting out of a thundercloud. Compared to the cloud's own charging rate, the amount of neutralizing charge that even massively large, practical size, arrays could aim at the cloud, would be trivial even if the sub and surrounding cloud circulations permitted delivery of the charge to the base of the cloud.

These circulations would not in general permit delivery of corona discharge to the cloud base except in the case where the corona source was directly beneath the strong updraft region of the cloud with the additional proviso that the cloud was in the evolutionary part of its cycle where the updraft existed. Even in this case, it would not follow that cloud electrification would be attenuated. According to one theory (Grenet & Vonnegut) that is a strong contender as an explanation for charge generation in thunderclouds, cloud electrification requires and would be intensified, if positive charge were fed into the base of the cloud.

In whatever way a corona point works, if it does so at all, in suppressing lightning, it can hardly be by neutralizing the charge of the cloud. If all our estimates are wrong and charge neutralization is an explanation, then one might argue that on the estimate of one microampere of corona discharge per tree that a reasonably dense forested area is covered with a natural corona array and that the forest should not be struck by lightning. Trees of a forest are struck by lightning and the distribution of strikes to various species of trees furnishes some interesting data for interpretation.

What is one finally to say about the performance of corona point arrays for prevention of lightning? The ONR prefers at this time to take no categorical position as to the performance of the arrays. We do offer for whatever help they might be, the various reports, papers, and discussions in this volume to those who have to make decisions about the installation of devises for lightning protection. The reports of the Atlantic Science Corporation contain findings based on theoretical analysis, instrumental measurements, photo observations, and detailed examination of log books at government and private installations that are as exhaustive as funds would permit. These reports, negative in their conclusions, were procured under contract to the ONR with funding assistance from the FAA. Professor Olsen's observations and measurement on field conditions and corona-point array performance was funded by the Air Force. Dr. Golde's and Dr. Stringfellow's views were solicited for inclusion among the contributed papers.

From the verbatim recordings of the discussions of corona-point arrays and related topics one can find expressions of conviction without reservation that such devices do not work to statements of guarded skepticism about their performance. The late Dr. Seville Chapman who was an authority on corona-point physics allowed that LEA must be doing something right to have so many satisfied customers. He particularly noted the importance of improving the grounding and the addition of RF chokes to lightning prone structures. His numerical data and report of experimental work on single and multiple corona points showed however that multiple point arrays have no advantage over single point in terms of current dissipated.

To whatever extent we succeeded in opening the questions of lightning protection by the various means presented, we owe thanks to many people. Among them are the various scientists who devote attention to the problems of atmospheric electricity and who journeyed to the Johnson Space Center to participate in this review. Their names are in the list of attendees in this report. We owe special thanks to Mr. Donald Arabian who takes active and earnest interest in the problems of lightning hazard to NASA launch operations and vehicles. Mr. Arabian arranged for the hosting of the review by the Johnson Space Center and the recording of the discussions. We also thank Bill Durrett and his collegues for their report on the performance of corona-point arrays at the KSC. Additionally, we thank Marlin Fostrum for his similar report on the performance of the corona-point arrays at Eglin AFB.

We owe particular thanks to Mr. Roy Carpenter of LEA who attended the review to explain his product and to detail performance data on his numerous installations. He answered many critical questions in detail and provided much specific data about his installations. Though at the end of the questions

and discussions he professed not to understand specifically how his product performed its intended task to prevent lightning, he did offer testimonials from numerous satisfied customers and a record of 178 installations which he regarded as successful with questionable performance on less than about ten percent of these. (We are obliged to note that both KSC and Eglin AFB are not sources of testimonials). Though this is not the kind of evidence acceptable to the scientific community, there is no reason to doubt the sincerity of Mr. Carpenter's belief in the ability of his product to prevent lightning. He replaces installations he regards as defective and warrantees his product to at least the extent of the cost of the installation for any damage that occurs subsequent to installation.

We thank also members of industry who attended our review and for their encouragement and interest in this research. And finally we thank both Dr. Golde and Dr. Stringfellow who evinced enough interest in our review to prepare comment for inclusion among the papers here presented.

J. HUGHES
ONR
31 Jan 77

AGENDA

0830	Welcoming Remarks, Don Arabian, Lyndon B. Johnson Space Flight Center
0835	Introduction, J. Hughes, ONR
0840	Commercial Products for Tall Structures Exposed to Lightning, Roy Carpenter, LEA
0910	KSC Report on Mast and Tall Structure Protection Against Lightning
1000	Rosman Report on Mast and Tall Structure Protection Against Lightning, Speaker to Be Announced
1030	Eglin Report, Marlin Forstrum
1100	Theoretical Studies of Mast Top Geometry for Lightning Dissipation, C. B. Moore, NMIMT
1115	Theoretical Studies of Corona from Tall Structures, Sigrid Llewellyn, ASC
1130	ONR Contract Report on Field Observations and Measurements at Eglin AFB, Don Olson, Univ. of Minnesota, Duluth
1200	Break for Lunch
1330	ONR Report Field Observations, Measurements, and Case Histories, Rodney Bent, ASC
1430	General Discussion
1700	Review Convened

ATTENDEES

Lightning Protection Technology
for Tall Structures
6th November 1975

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R. Gadbois	NASA/Johnson Space Center Houston, Texas

170 SYSTEM YEARS OF GUARANTEED LIGHTNING PREVENTION

by

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of

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Downey, California 90241

November 6, 1975

170 SYSTEM YEARS OF GUARANTEED LIGHTNING PREVENTION

INTRODUCTION

This technical paper has been prepared to present results rather than theory. The field of lightning protection is one that is not considered an exact science. Its early history has been replete with various forms of charlatanic escapades; as a result, with the introduction of any new form of protection, there is an unusual level of attendant suspicion. This is particularly true when the claim is to prevent lightning. At this point, the claimant relationship to God is usually questioned, in a half joking manner.

Lightning, as with any other problem, can be treated on the basis of either a remedial principal, or a preventative principal. The remedial concepts are all based on the assumption that lightning must occur and therefore the engineer must deal with its manifestations. The problem is that a protection concept, based on this premise, must be predicated on the engineer's ability to identify and adequately define the deleterious manifestations. The continued losses from lightning damage, throughout industry, attest to the ineffectiveness of this approach.

A preventative concept is based on the premise that lightning does not have to form at least within the area of concern. Given that this premise is true and the objective can be achieved within an acceptable risk level, there is no need to identify and deal with any of the lightning characteristics. The Dissipation Array System is predicated on the principal that lightning strikes to areas of concern can be prevented. This paper presents some evidence toward vindication of that premise.

THE SITUATION

To establish a common basis of communications, it is desirable to identify the situation within which a Dissipation Array System must function. Basic to this is the realization that the Array <u>does not</u> deal with lightning; but rather, the situation that precedes lightning. Although the causes have not been agreed upon, the resulting situation has at least been bracketed. A compilation

of the various measurements have been made by various authors; J. Alan Chalmers[1] provided much of the following data:

1) Charge range = 2 to 200 Coulombs

2) Peak currents = 2 to 350 Kiloamperes

3) Discharge time = 1 to 100 Milliseconds

4) Rise time = 1 to 10 Microseconds

5) Relaxation or recharge time = 40 seconds* to many minutes

6) Field strength prior to stroke = 3 to 5 Kilovolts per centimeter

7) Cloud/Earth potential at breakdown = 25×10^6 to 10^8 Volts

8) Point discharge potential ≥ 10 Kilovolts

*Inaccurate estimate due to measurement techniques.

These data, together with Figure 1, define the situation within which a lightning prevention system must function. The data also define upper boundaries below which a preventative system must operate to assure lightning prevention. The illustrative figure points out the fact that as the charged clouds move into the area, they induce an opposite charge on the earth's surface and any intervening structure. The resulting electrostatic pressure is exerted on the separating air space, establishing the previously defined field. Within this situation, the Dissipation Array must function to establish and maintain an environment not conducive to the formation of lightning, within the area of concern.

THE DISSIPATION ARRAY CONCEPT

The Dissipation Array System is based on a proliferation of the electrostatic phenomena known as the Point Discharge Principal. The specific system designs are proprietary with LEA. The specific protective mechanism results from the significant flow of ion current, created by the thousands of special points, designed, deployed and oriented to maximize the flow of ion current, in the presence of atmospheric electricity. A Ground Current Collec-

(1) "Atmospheric Electricity, J. Alan Chalmers, Pergamon Press, 1965.

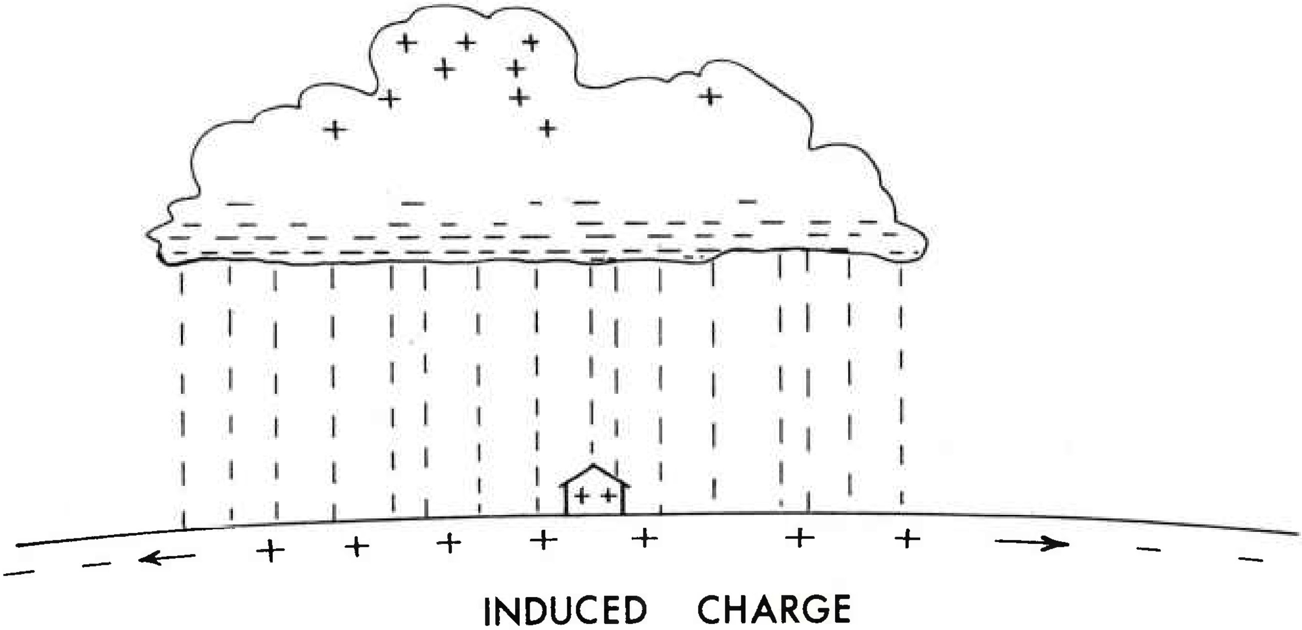


FIGURE 1, CHARGED CLOUD INFLUENCE ON SURFACE FACILITIES

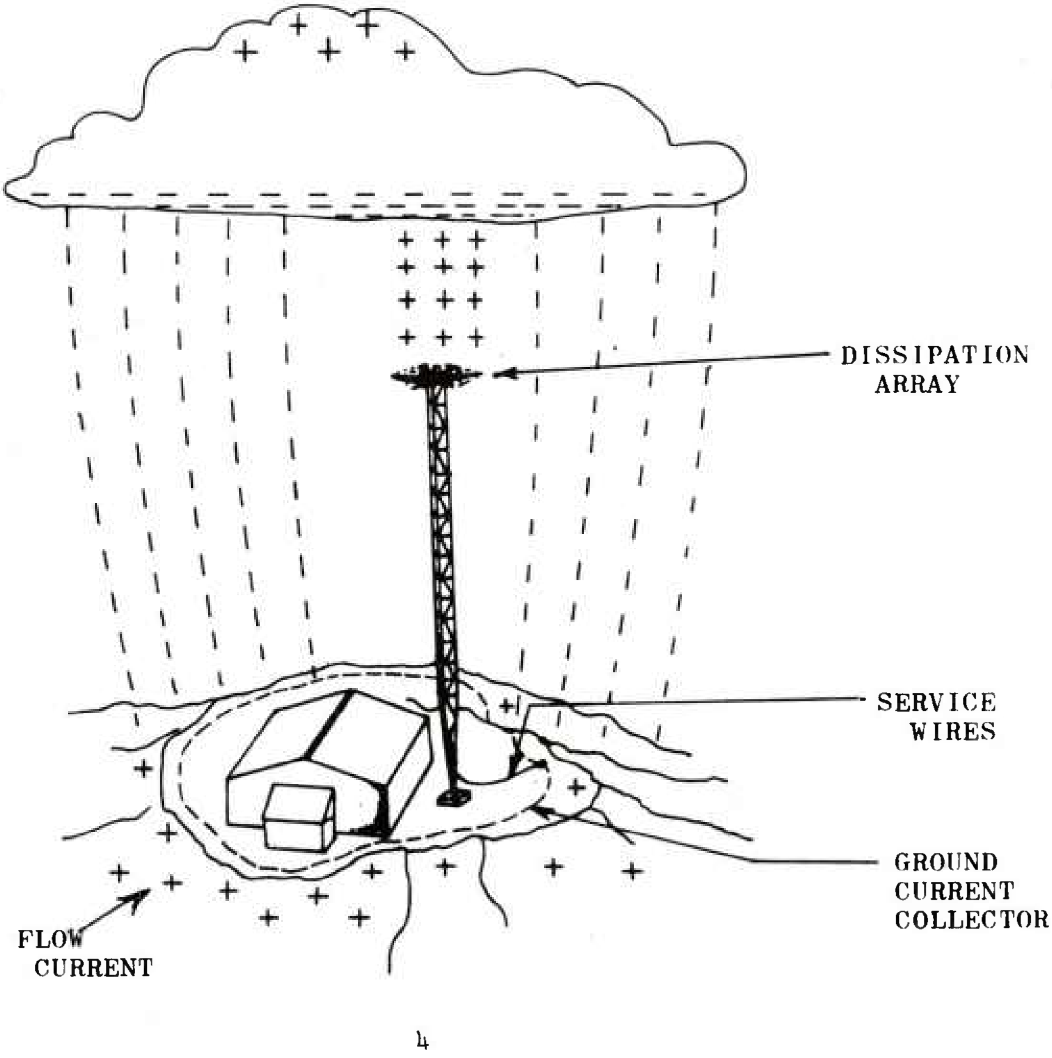


FIGURE 2, OVERALL FUNCTIONAL CONCEPT, DISSIPATION ARRAY SYSTEM

tor provides a preferred path for the collection of the induced charge and its flow to the dissipator. The basic concept is illustrated by Figure 2.

There is some disagreement over exactly how the Dissipation Array performs its preventative function; several possibilities exist, any or all of which could be true to some degree. It has been shown that a single Dissipation Array System can generate current levels of over 300 milliamperes at peak. Further, dissipation current history and visual observations taken by NASA at one site in Florida, indicate that storms passing directly over the site were significantly altered. The concentration of dissipation current seemed to degenerate the storms as they arrived over the protected area.

It is believed that the preventative function of the array system is the result of one or all of the following:

(1) The cloud charge is reduced proportional to the flow of current.

(2) The field gradient is reduced by the flow of ions through the intervening air space between the facility and the cloud; i.e. the equivalent "IR" drop.

(3) The mass of ions produced act as a shield, even for adjacent facilities or land mass not directly tied to an array component.

Since there is some controversy over how a Dissipation Array prevents lightning, and LEA is not disposed toward revealing all the design parameters; it is perhaps more expedient to consider the results, on that basis alone. It is now an evident truth that lightning strikes have been successfully prevented; and under the most adverse of circumstances. The level of confidence is such that each customer is given a Warranty, backed by an international underwriter.

PERFORMANCE DATA

Since the first installation accomplished by LEA in November 1972 unto this writing, 111 Dissipation Array Systems have been installed in various parts of the world; and in isokeraunic levels varying from a low of 10 to a high of 260. Table 1 presents a

TABLE I

LEA HISTORICAL DATA

INSTALLATION DATE	NUMBER OF ARRAY SYS.	FACILITY TYPE	ISOKERAUNIC LEVEL	PRE-INSTALLATION HISTORY
12/71	1 Conic	UHF-TV	10	Many
8/72	1 Umbrella	Microwave	12	3/yr.
5/73	1 Umbrella (large)	UHF COM.	78	120/yr.
3/73	2 Umbrella 4 Tank Mtd	Oil Process	260	20/yr. *
9/73	16 Various	Space Data	56	4/yr. *
5/73	5 Panels	Broadcast	31	25/yr.
8/73	1 Umbrella	Water Flow Control Sys.	35	3-5/yr.
3/74	4 Various	Sled Track	78	Unknown
10/73	1 Augmented Guy	VHF-TV	13	Many Outages **
9/73	1 Umbrella	Cable TV	42	(New)
11/74	Dissipation Stripping	Large Bldg.	91	(New)

LEA HISTORICAL DATA (CONT)

INSTALLATION DATE	NUMBER OF ARRAY SYS.	FACILITY TYPE	ISOKERAUNIC LEVEL	PRE-INSTALLATION HISTORY
11/73	1 Augmented Guy	VHF-TV	46	Many outages
11/73	1 Umbrella	Substation	91	3-5/yr. outages
1/74	2 Panel	Broadcast	85	Many outages **
11/73	1 Umbrella 6 Panels	AM/FM	44	Many outages **
6/74	33 Panels	Parking Lot	91	Some **
4/74	1 Umbrella	Met Tower	23	(New)
7/74	4 Various	Launch Acq.	88	2/yr.
5/74	5 Various	Space Data	32	Many **
5/74	1 Panel	Met Tower	33	Several/yr. **
6/74	1 Panel	Met Tower	40	5/yr. *
7/74	1 Panel (large)	Met Tower	88	2/yr.
9/74	1 Panel	Met Tower	32	(New)

LEA HISTORICAL DATA (CONT)

INSTALLATION DATE	NUMBER OF ARRAY SYS.	FACILITY TYPE	ISOKERAUNIC LEVEL	PRE-INSTALLATION HISTORY
8/74	1 Panel (large)	Broadcast	50	Many outages **
10/74	7 Panels	Broadcast	70	Many outages
9/74	1 Panel	Met Tower	91	(New)
9/74	1 Panel	Met Tower	90	(New)
8/74	6 Panels	Broadcast	40	Many outages **
10/74	1 Umbrella	Met Tower	37	Significant losses
10/74	1 Umbrella	Met Tower	90	(New)
10/74	1 Panel	Met Tower	44	(New)
12/74	1 Umbrella	FM Tower	50	Outages & Damage
1/75	1 Umbrella	Met Tower	55	Major losses
2/75	Multi-Panel	Launch Pad	88	41/yr.
2/75	1 Umbrella	Met Tower	90	(New)

summary of the pertinent data with respect to these installations. Although not all of them have good preinstallation strike history; all are known to have had no lightning strikes, after once being certified. It may be of particular interest to consider details and peculiarities of some of these installations.

Communications Site C-9, Eglin AFB Florida

On the site known as C-9 is a 1200-foot tower supporting a communications system for the Air Force Weapons System's test range, plus other solid state electronics located at several levels between the top and the 300-foot level. The isokeraunic level in this area is estimated at 88.

The station history is replete with losses and strike sightings. The station operators report seeing strikes from every storm passing overhead; further, they report numerous multiple strikes during each of these storms. The electronics systems operator gave up using his system after a year of continued losses. He even reports losses when no lightning was reported; these resulted from atmospheric induced transients.

In May 1973, LEA completed installation of an Umbrella Array System as illustrated by Figure 3. For the subsequent 15 months period, the system was instrumented and monitored continuously by Air Force personnel. No strikes were noted during this period; conversely, high dissipation currents were recorded regularly. Figure 4 presents a segment of one such chart; the dissipation current flow averaged 2200 microamperes during this period.

During the spring it was noted that during several storms the cloud base was actually below the top of the tower, a situation the array was not designed to cope with. It was then predicted that during the low altitude spring storms a "side stroke" could penetrate the protected area. Twenty-two (22) months after the installation was completed, such an event occurred, under the same circumstances. This was the only strike to that tower, in a period where about 220 strikes could be predicted; none were encountered.

At a later date, July 1974, LEA elected to change the array at no cost to the USAF. The old array was removed on Monday and by Thursday of the same week, five strikes were observed; two of which caused major damage. The new array was installed by a crew working overtime. No strikes have been subsequently recorded and no damage has been experienced.

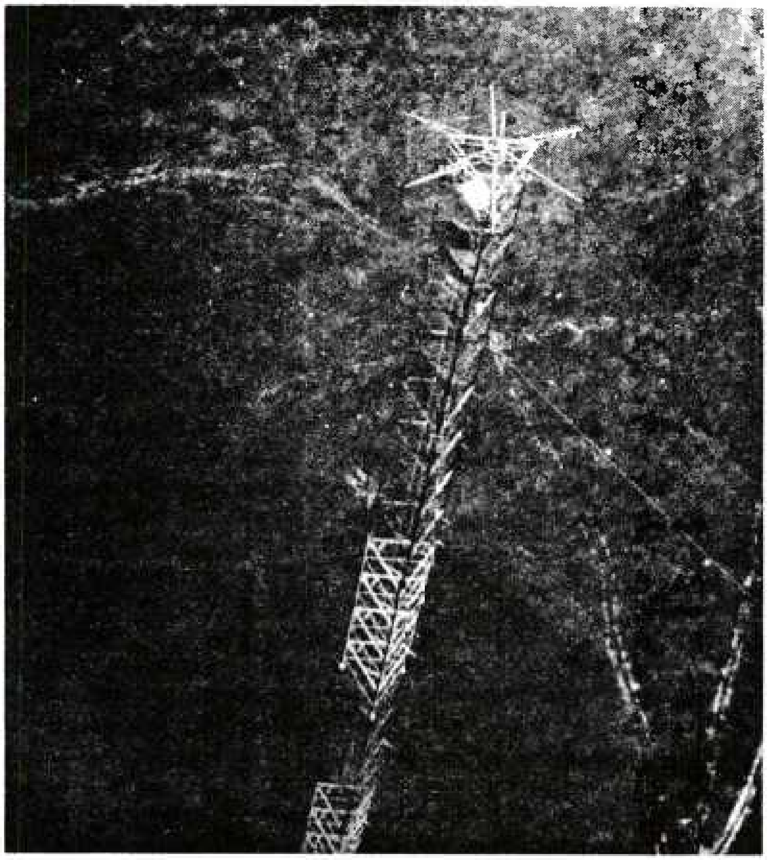


FIGURE 3, 1200-FOOT TOWER, C-9, EGLIN AFB, FLORIDA

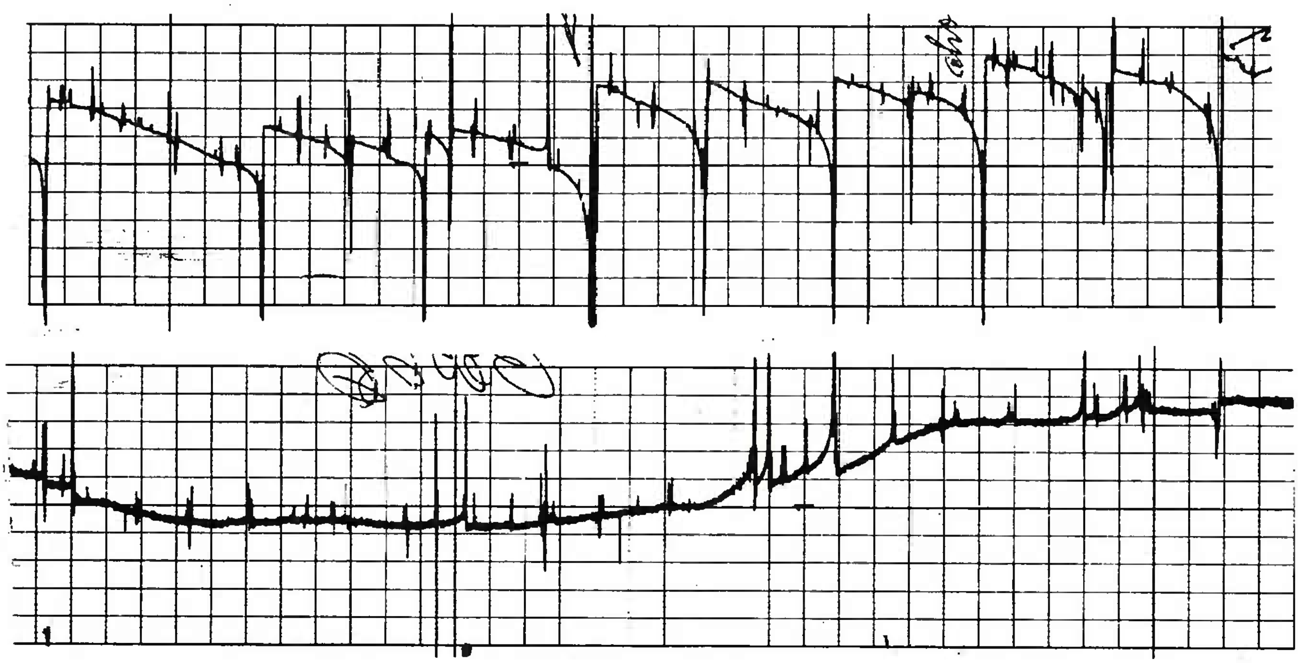


FIGURE 4, C-9, EGLIN AFB FLORIDA, DISSIPATION CURRENT HISTORY

Radio CKLW Windsor, Ontario, Canada

CKLW's Antenna System is composed of five 300-foot towers, situated on a peninsula that juts out into Lake Erie. The land surrounding the station is flat; the towers represent the highest elevation for miles around. The isokeraunic level is reported at 31 by the World Meteorology Organization; however, the station engineers state that in the immediate area it is significantly higher. The station averaged over 25 outages per year due to lightning strikes; and these do not include momentary outages due to weak strikes or induced transients.

In March 1975, LEA installed Panel Arrays on each of the five towers, one such is illustrated by Figure 5. The system has to date passed through two years of no outages. The dissipation current from one tower has been used to activate a Lightning Warning and Control System which, in turn, activates a diesel generator. No recording of currents were made; however, measurements were made during several storms and peak currents of up to 20,000 microamperes were recorded.

KHOF-TV San Bernardino, California

Station KHOF-TV is situated on a 5,000-foot mountain peak, above the San Gabriel Valley of Southern California. The 50-foot slotted Wave Guide Antenna is mounted atop its 100-foot tower. Its history of lightning losses and strike history is unparalleled. Although its isokeraunic level is recorded as only 10, the station engineers protest that it is more nearly 30. Although the exact number of outages were not recorded, the losses were significant and the outages were many each year.

In December 1972, LEA installed a Truncated Conic Array, using the tower top as the apex of the array; the antenna rose fifty feet above the array top. The array was designed such that the dissipators were parallel with the lines of equal potential although the array was well below the uppermost elements. No strikes and no losses have been recorded at that station since the installation.

KOSI-FM Denver, Colorado

The FM transmitter is located high on the outer face of Lookout Mountain, overlooking the Denver Valley. The tower is only 100 feet high, supporting a twelve element FM antenna. Repeated strikes to the upper two or three elements would melt joints, burn out coax and destroy many solid state components in the FM

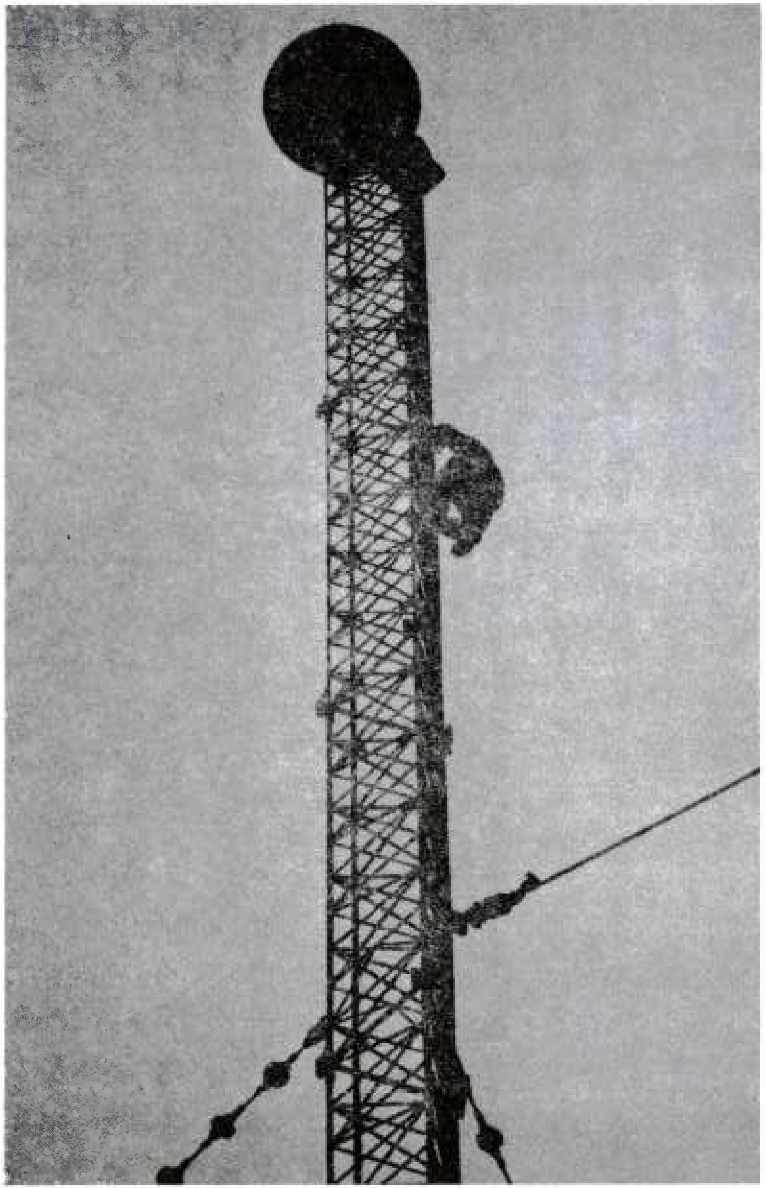


FIGURE 5, CKLW RADIO, PANEL ARRAY INSTALLATION

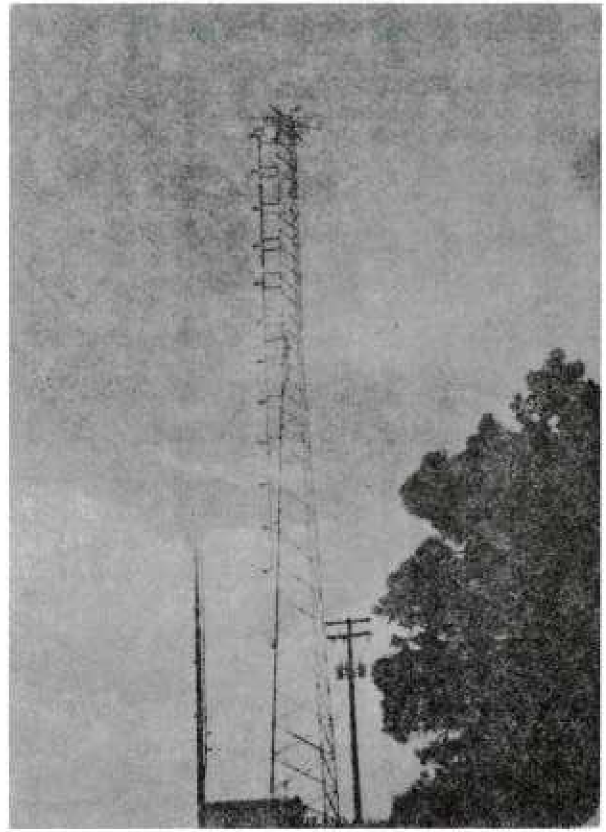


FIGURE 6, UMBRELLA ARRAY INSTALLATION KOSI-FM DENVER, COLORADO

transmitter. During the summer season, the station was off the air much of the time due to lightning activity.

In November 1973, LEA installed an Umbrella Array atop the tower as illustrated by Figure 6, and dug in a small Ground Current Collector. The results were gratifying, since that time no strikes, internal damage or antenna element losses have been experienced.

A situation similar to CKLW's existed with KOSI Radio. Their five tower antenna farm is located in an area called "Lightning Alley". After installation of Panel Arrays on each tower, no further outages or losses were noted.

NASA STDN Rosman, North Carolina

High in the Blue Ridge Mountains of North Carolina, NASA located the primary station for its Manned Space Flight Network. The site occupies an area of over 180 acres in a mountainous area where the isokeraunic level is recorded at 56. The station layout is illustrated by Figure 7. Note that major facilities are scattered throughout the area, with miles of cable interconnecting the outlying systems, the operations center and the main power plant.

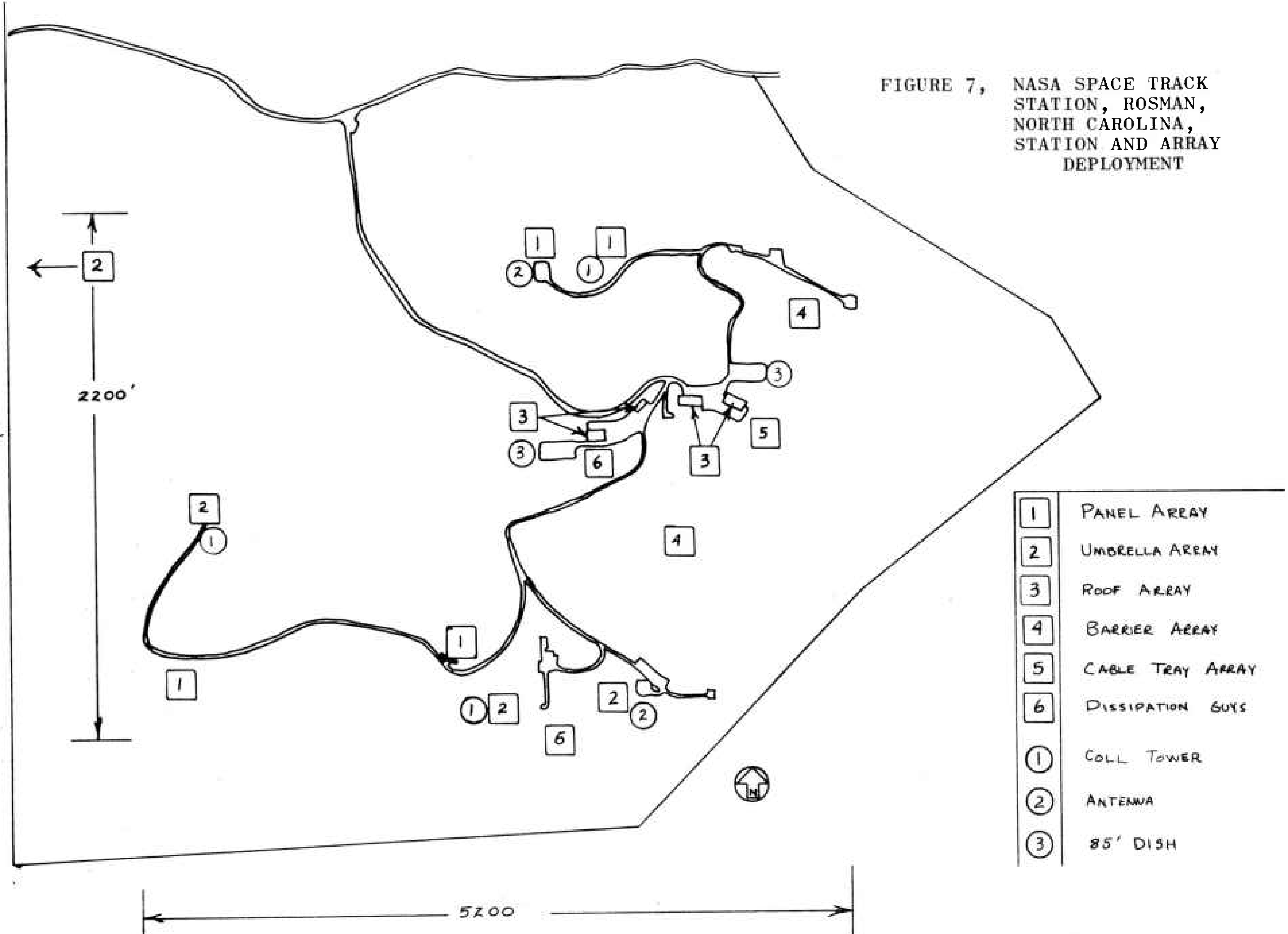
Since its completion, it developed a history of losses and outages, created by direct strikes and transients due to nearby strikes. They had buried literally hundreds of pounds of copper in the earth, in an attempt to achieve an acceptable ground and eliminate the hazard; all to no avail.

In August 1973, LEA completed what was to be the first phase of a two-step installation at Rosman STDN. As indicated on Figure 7, a total of 16 array systems were installed; three of these were added during the second phase. Several of the systems were instrumented immediately and monitored daily.

After the first years operation, it was found that no strikes had penetrated the protected area. However, transients were repeatedly penetrating some cables, at the far end of the facility (upper left of Figure 7). A survey of the area coupled with a study of the cable routing revealed that the transients were created by multiple strikes to a hill just outside the area of concern. At this point, offending cables passed within about 25 feet of the hill.

LEA returned and plowed in 2,500 feet of Ground Current Collector along the cable route, connecting it to two new arrays installed in the area. The results were gratifying; not only were further

FIGURE 7, NASA SPACE TRACK STATION, ROSMAN, NORTH CAROLINA, STATION AND ARRAY DEPLOYMENT



strikes eliminated from the area, but so were the harmful transients as well.

Dissipation current measurements for one of these systems reached instrument saturation at 6,000 microamperes, for extended periods. See Figure 8. Observers report seeing several of the systems (not instrumented) actually glow as storms pass directly overhead.

NASA Launch Acquisition Station, Merritt Island, Florida

The Merritt Island Launch Acquisition Station occupies about 20 acres of land on the western end of the Kennedy Space Center, Florida. The isokeraunic level is reported at about 90. Both direct strikes and induced transients presented a major threat to station operation.

In July 1974, LEA completed installation of five different Dissipation Array Systems on the 20 acre facility, as shown by Figure 9. All five systems were instrumented and monitored 24 hours per day by NASA personnel.

Subsequent to the first storm, the station director reported the results of visual observations. He indicated that as the storm moved into the station area, it seemed to degenerate. Later, a study of the recorded dissipation current flow data substantiated his claims. A study of the chart recordings for the data showed that the dissipation current climbed steadily as the storm approached, with many transients indicating distant discharges. As the storms reach the station area, all lightning in the area ceased, but the dissipation current continued to rise until the storm was overhead. The current in one array rose to a level of 150 milliamperes, maintaining this level until the storm moved out of the area. This phenomena repeated itself for each time a storm passed directly over the station, no strikes or transients were recorded on or near the station. The total charge dissipated was found to peak out at between 2.5 and 5.8 Coulombs per minute, while the storm was in the area.

Rio Pinar Substation, Orlando, Florida

Rio Pinar is the main switching station for the Florida Power Company's central Florida Transmission and Distribution System. Its early history was plagued with outages, often at times when the control capability was vital. Outages resulted until a man could be dispatched to perform the switching operations manually.

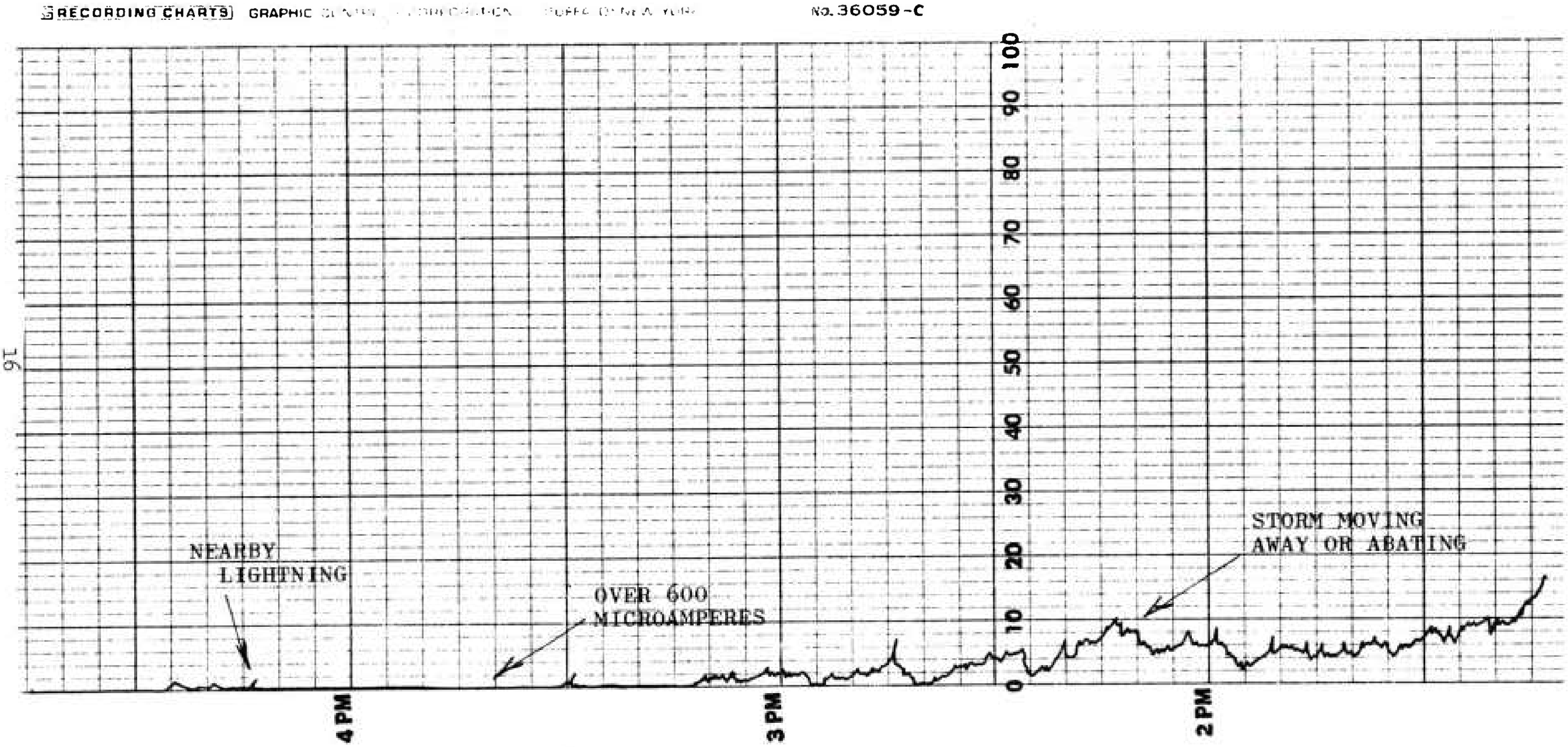
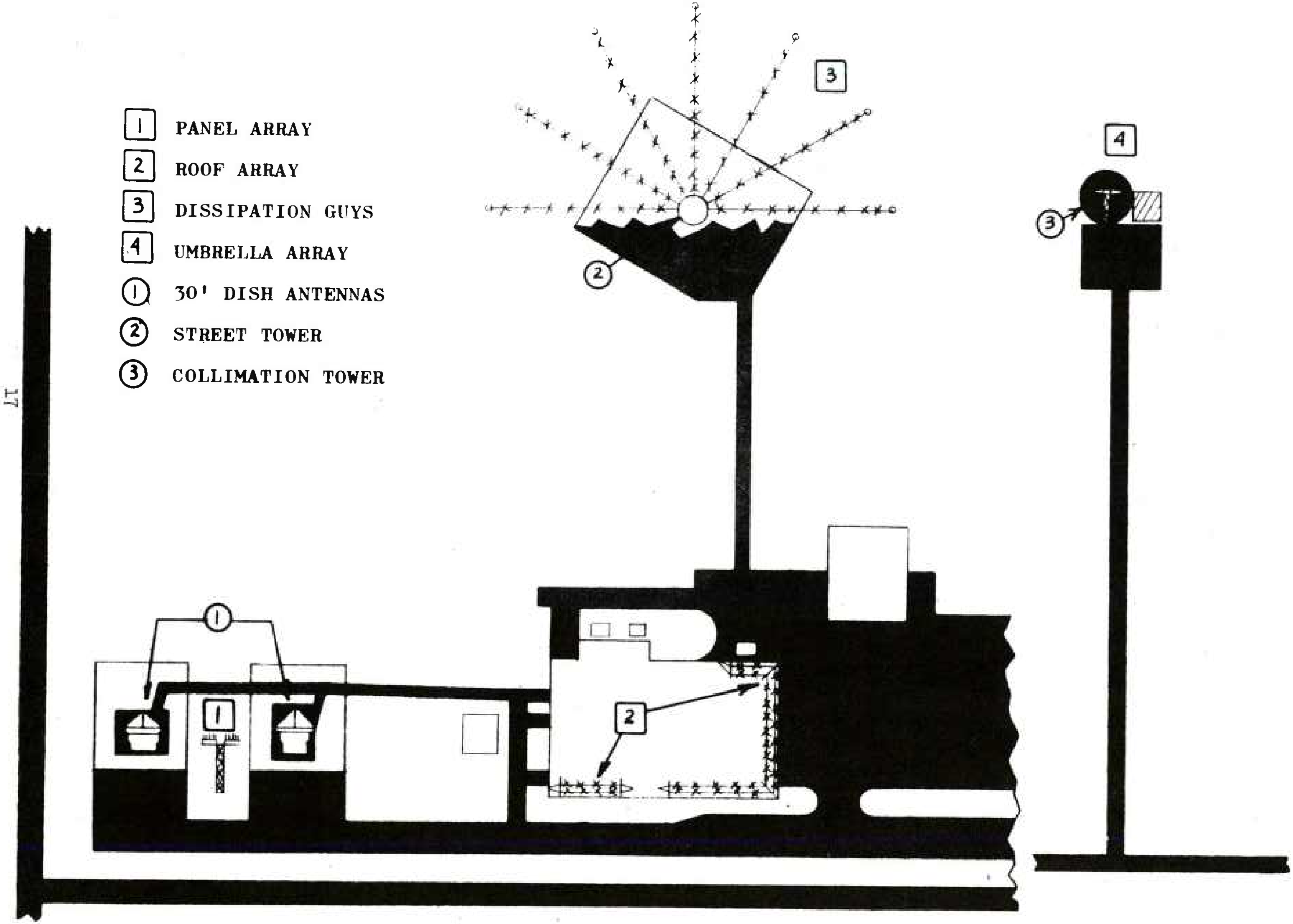


FIGURE 8, OVERHEAD STORM, PANEL ARRAY CURRENT, MAY 10, 1974 - SITE C-9, EGLIN AFB, FLORIDA


1 PANEL ARRAY
2 ROOF ARRAY
3 DISSIPATION GUYS
4 UMBRELLA ARRAY
1 30' DISH ANTENNAS
2 STREET TOWER
3 COLLIMATION TOWER

The substation is illustrated by Figure 11; it is about 800 feet long and about 400 feet wide. Near one end is located a one hundred foot command and control tower. LEA mounted a large Umbrella Array atop that tower, integrating both the substation ground mat and the control station ground mat into a Ground Current Collector subsystem. The installation was completed November 1974 and instrumented by Florida Power Company personnel. No strikes were recorded, or outages experienced since the installation was completed. Conversely, the recordings taken were considered positive proof of the systems capability to prevent strikes. A sample of these data are presented in Figure 12.

<u>Union Oil of Indonesia</u>

On the Island of Kalimantan (formerly Borneo), Union Oil Company of Indonesia carved a 420 acre facility out of the jungle. It is near the village of Santan, just under the equator. The land is flat and on the eastern shores of the Makassar Straits. The best estimate for the isokeraunic level is about 260. These data, when used to estimate the probable number of strikes to the facility area, reveal a potential hazard rate of over 20 strikes per year. Union elected to protect the area with the Dissipation Array System as the facility was being constructed. Work was completed in March 1973; the layout is illustrated by Figure 13.

The Dissipation Array System consisted of four Tank Arrays providing over 25,000 dissipating points each. In addition, one large Umbrella Array was used to protect the Regenerator area and one to protect a 300-foot communications tower.

In the two years of operation, no lightning activity has been observed in that general area; no losses have occurred from lightning activity.

DATA IMPLICATIONS

The phenomena known as lightning is normally unpredictable, except on a statistical basis. Therefore, any claims made on the basis of a small sample size is suspect. Given this premise alone, it is difficult to take any one isolated situation, and on the basis of one to three years of no lightning losses, prove that lightning has or can be prevented. However, that is not the case with the LEA Dissipation Array System.

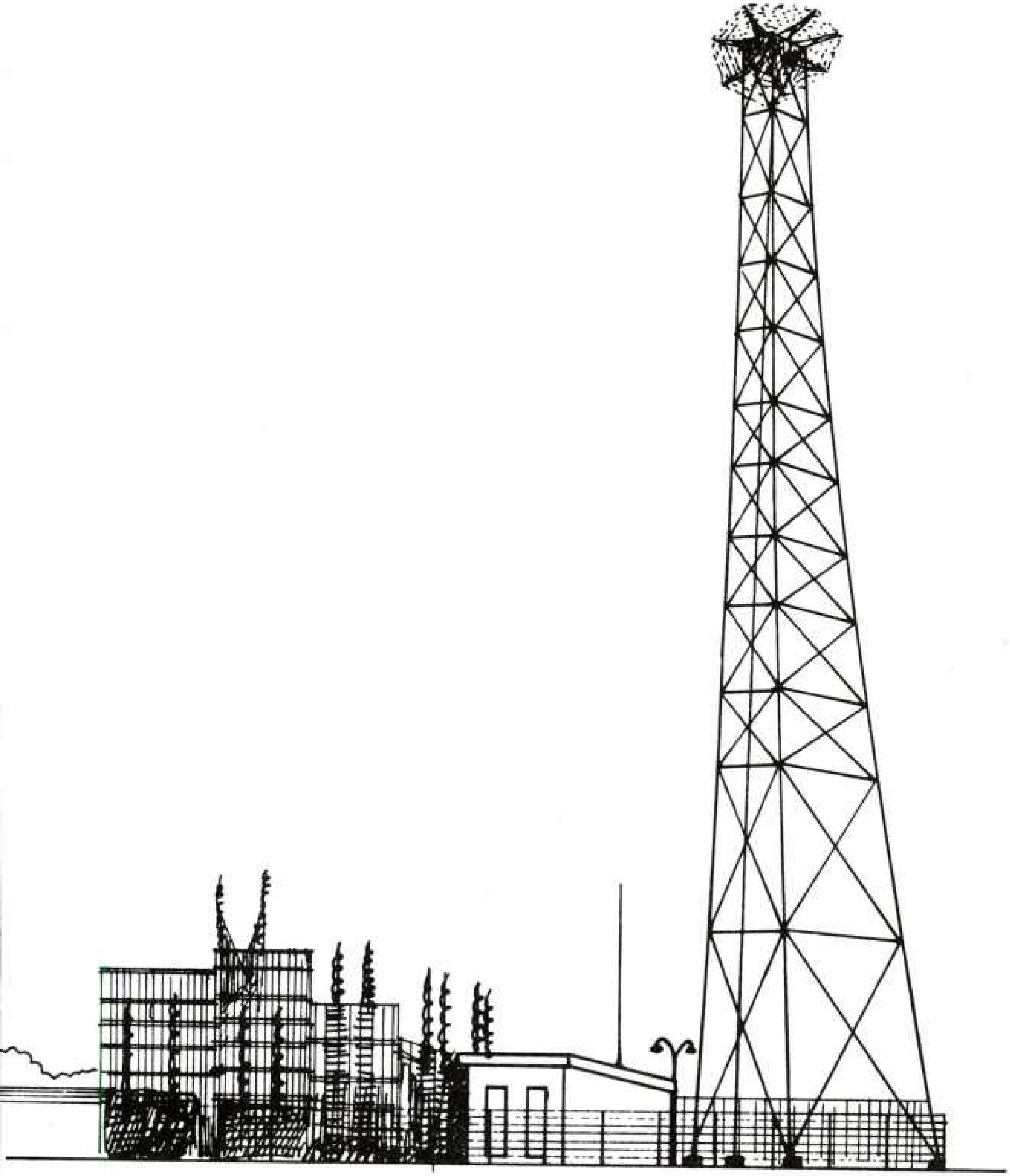


FIGURE 11, RIO PINAR SUBSTATION LAYOUT, ORLANDO, FLORIDA

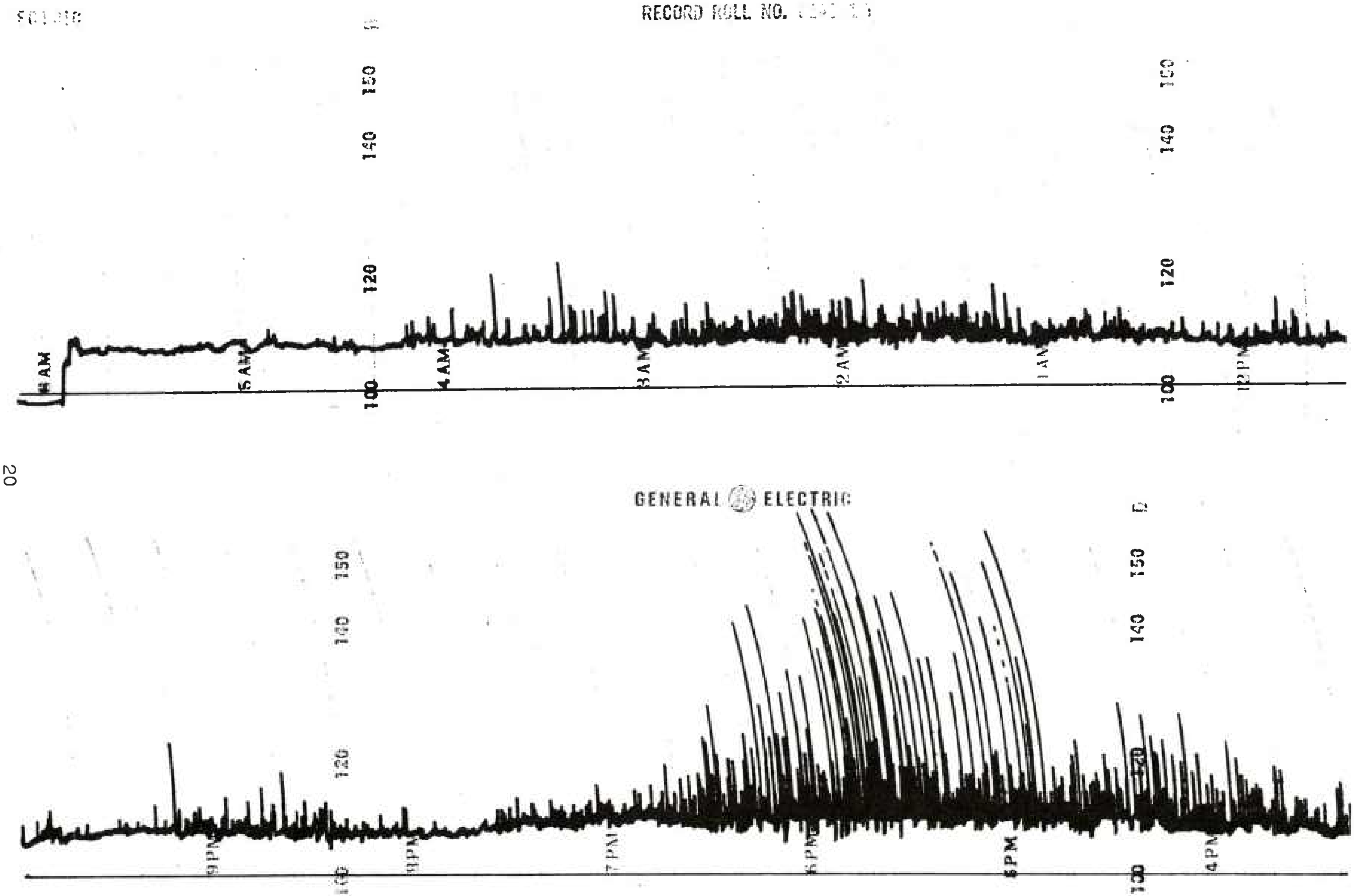


FIGURE 12, DISSIPATION CURRENT RECORDING, RIO PINARD SUBSTATION

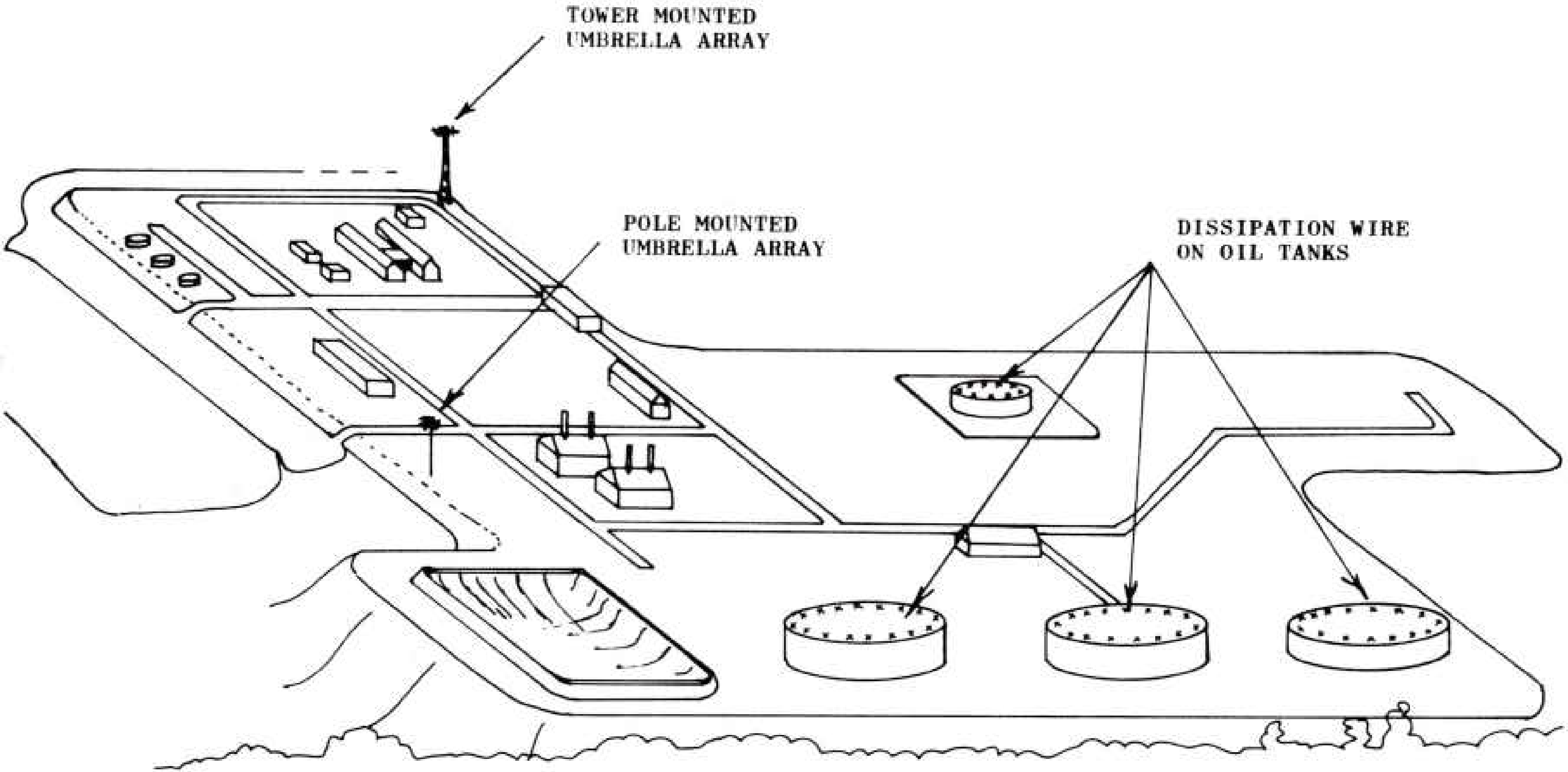


FIGURE 13, UNOCAL OF INDONESIA, SANTAN FACILITY, KALIMANTAN, INDONESIA

Three factors of significance mitigate such a conclusion with respect to Dissipation Array history:

(1) LEA systems have accumulated in excess of 170 system-years of no strike history, in isokeraunic levels varying from 10 to 260.

(2) The preponderance of systems were sold to customers who had a continuous history of severe losses; and in all these cases, were unable to resolve the problem any other way.

(3) Recorded data indicates the systems are dissipating significant amounts of ion current and are performing their intended function, and in the manner predicted.

If we estimate the Dissipation Array reliability on the basis of simple statistics, i.e. 170 system-years alone, the value would be only .994; that is there is no more than 6 chances in 1000 of a Dissipation Array admitting a strike within the protected area in any given year. However, this is very inaccurate since it does not consider the exposure hazard.

If we consider exposure in the estimator, the array at C-9 alone provides a reliability of .996, even if we include consideration of the one side stroke outside its functional capability. If we add to these, data from five other systems, where records are available, the reliability estimator exceeds .998. If all the systems were used, on the basis of their individual probabilities the reliability estimator would exceed .9999.

One other factor of particular interest to communications system users: During the tests conducted at the USAF C-9 Communications site, it was discovered that the Dissipation Array System actually improved the effective Noise Figure of any receivers using the protected tower for mounting its antenna. This phenomena is the result of lowering the difference of potential between the tower top and the surrounding field. The lower potential resulted in a lower potential noise leaking off the tower; and/or a lower induced transient into the receiver due to local atmospherics.

CONCLUSIONS

Results are the criteria upon which sound decisions are made. The theoretical aspect of any situation is important in the formative

stages of any new innovation or project; but in the final analysis, the decision maker must depend on results. Some engineers may tend to rely on "the way we always did it" or the "tried and true", to avoid "making waves". However, the manager who makes his decisions on the basis of results, will tend to select new innovations that will assure the desired results. Such has been the case with the Dissipation Array. The initial reticence toward change has been overcome by results and a rising number are using the system. Finally, all have been given a guarantee which assumes liability for losses resulting from ineffective system performance.

The reader is invited to examine the evidence:

(1) A no-strike record with 111 systems installed to date.

(2) An estimated reliability exceeding 0.9999, a proven reliability exceeding 0.998.

(3) Confidence expressed by a Warranty backed by an international underwriter.

The basic conclusion is obvious, after 200 years of controversy, lightning prevention has been proven a reality. A communications site designer can spend between $1,200.00 and $6,900.00 for a turnkey system and save up to $60,000.00 in losses. One customer actually lost $60,000.00 in equipment in one strike. Others have had greater losses, when downtime was considered.

DISSIPATION ARRAYS AT KENNEDY SPACE CENTER

by

W. R. Durrett

of

NASA/Kennedy Space Center,
Florida 32815

November 6, 1975

JSC Meeting
November 6, 1975
REVIEW OF LIGHTNING PROTECTION TECHNOLOGY FOR TALL STRUCTURES

Dissipation Arrays at Kennedy Space Center
(W. R. Durrett, DD-EDD)

The questions concerning the use of dissipation arrays at Kennedy Space Center (KSC) first came into clear focus on June 21, 1971, after the Apollo 15 mission then in checkout sustained several strikes to the Launcher Umbilical Tower (LUT) and some hardware damage occurred. Several methods of improving the lightning protection at the pad were investigated by the KSC Lightning Study Team and reported on to KSC management; dissipation arrays were included. The interest in dissipation arrays continued on through 1972 and 1973, particularly for the possible protection of the Shuttle during rollout from the VAB to the pad. On November 15, 1973 a review was held at KSC on potential lightning problems that might be encountered by the Apollo-Soyuz Test Project (ASTP). As a result of this review, KSC was instructed to investigate the dissipation array concept for possible ASTP use. A letter to KSC from the Johnson Space Center on May 21, 1974 reiterated the request for this study in connection with the Shuttle program.

KSC has dissipation arrays in four separate locations:- (1) 150 meter weather tower, (2) Unified S-Band Station, (3) Mobile Service Structure, LC-39, and (4) Mobile Service Tower, LC-41 (Cape Canaveral Air Force Station). The 150 meter weather tower is approximately 2-1/2 miles west of the ocean and almost due west of Pad B, LC-39. The Unified S-Band Station is approximately 8 miles west of the ocean, 2-1/2 miles east of the Indian River, and 8 miles south of Pad B. The Mobile Service Structure is approximately 1/2 mile west of the ocean when in place on Pad B; it is about 2 miles west of the ocean and south of Pad B at its park site. The Mobile Service Tower, LC-41, is approximately 1/2 mile west of the ocean and 3 miles south of LC-39. The handout and accompanying slide photos show these arrays.

150-Meter Tower

The 150 meter weather was erected in the early days of KSC to provide wind data up to the 500 ft. level. It is a triangular guyed tower with 6 guy wires at 120^{o} angle running perpendicular to the tower faces. It has a nine year lightning strike history which extends back to 1965. The history is derived from the installation of magnetic slugs on top of the tower on each of the three tower legs. Over the period 1965-73 (9 years), the slugs have recorded 18 strikes as follows:

1965 - 3	1970 - 1
1966 - 4	1971 - 3
1967 - 0	1972 - 3
1968 - 2	1973 - 0
1969 - 2	

Since the magnetic slugs record cumulatively and can only report the strongest magnetic field they sense, they do not give a true report of how many strikes the tower received. The 18 strikes, therefore, must be considered a minimum number.

Three galvanized steel dissipation array panels procured from Lightning Elimination Associates were installed on top of the tower June 21, 1974. At the conclusion of work that day, a temporary ground was attached between the panels and the tower ground network (the LEA installation was not complete). On June 22, 1974 the tower received a lightning strike as evidenced by the magnetic slugs on the outer guy wires of the tower and the loss of some tower wind velocity instrumentation. The LEA grounding system was installed subsequently and the installation completed June 30, 1974. The arrays were mounted insulated from the tower structure, and a downlead run down the tower to ground through a load box to permit monitoring of the array current. The complete job was LEA designed and installed.

On June 15, 1974, we received a report from LEA that the array on the weather tower should be considered as defective. Excessively thick galvanizing, blunting the array points, reportedly had been noticed on another panel galvanized at the same time as the KSC panels and LEA felt the KSC array should be considered to be similarly unsatisfactory.

On July 18, 1974, the tower was struck twice within a 12 minute period. This was documented by magnetic slugs and by TV pictures. Subsequent examination of the ground lead from the array down the tower to the instrumentation load box at the tower base showed two arc-over points where a short circuit had occurred between the downlead and the tower structure. LEA replaced the galvanized panels with stainless steel panels as of July 30, 1974. The stainless array was struck on July 20, 1975 and on October 3, 1975. The July 20 strike was verified by magnetic slug readings, and the October 3 strike by the loss of wind velocity instrumentation, magnetic slug readings, and a new arc point between the array downlead and the tower structure.

Unified S-Band Station

The Unified S-Band Station installation was made by LEA in June 1974 under contract to the Goddard Space Flight Center. Four different instrumented array designs were installed at four different locations on the station site. I will not discuss this installation in detail - Dr. Bent has made a study of it and will report on it separately.

The Unified S-Band Station has no lightning strike history. It has received no strikes before or since the LEA installation. It has not been struck at any time from its commissioning in 1966 until the present.

Mobile Service Structure, LC-39

The Mobile Service Structure installation does not involve LEA. There are four different dissipation array designs mounted on it which were designed by KSC and installed as of July 24, 1974 for the purpose of investigating concepts. The Mobile Service Structure has no known strike history before 1972 when the existing lightning mast was installed. (Earlier, magnetic slugs were installed but were in inaccessible locations and not serviced regularly.) Since the lightning mast installation, the Mobile Service Structure has been struck by lightning as given below:

		VERIFIED BY:			
Date	Location	Slugs	Ped. Current	Induced Voltage	TV
Aug 9, 1972	Parksite (alone) (mast up, but instr. not in)			X	
May 24, 1973	LC-39, Pad B (with LUT)	X	X	X	X
June 17, 1973	LC-39, Pad B (with LUT)	X	X	X	
July 29, 1973	Parksite (alone)	X	X	X	
Aug 1, 1973	Parksite (alone)	X	X	X	
May 5, 1974	LC-39, Pad B (alone)	X	X	X	
May 12, 1974	LC-39, Pad B (alone)	X	X	X	
July 24, 1974		Dissipation arrays mounted on MSS			
July 25, 1974	LC-39, Pad B (alone)	X	X	X	
Aug 21, 1974	LC-39, Pad B (alone)	X	X	X	X
May 9, 1975	LC-39, Pad B (with LUT)	X	X	X	X

The strikes given are those to the Mobile Service Structure itself; it does not include strokes to the LUT when both LUT and MSS are on the pad. The LUT's lightning mast is somewhat taller than the MSS mast, and pad strokes usually hit the LUT, not the MSS.

Mobile Service Tower, LC-41

The installation on the Mobile Service Tower at LC-41 was made under the auspices of the Lewis Research Center on the request of the Langley Research Center for the protection of the Viking spacecraft. Ten LEA stainless steel panels were installed on top of the MST on February 26, 1975. These panels were not instrumented; they were fastened solidly to the structure and in May 1975 they were welded in place. The MST has an instrumentation

system which detects voltage in the structure measured from top to bottom, and induced effects from near misses will therefore be detected. On the strength of the magnitude of the recorded induced voltages, four assumed strikes to this tower occurred in 1974 (after installation of the instrumentation but before the LEA arrays). These strikes took place on May 3, June 11, June 22, and July 22, 1974. After the installation of the arrays, two assumed strikes occurred, on June 7 and June 16, 1975. The instrumentation system recorded several other events, many of which are known and documented near misses. Since there was little photo or TV coverage of the MST and the structure configuration did not yield itself easily to definitive locations for magnetic slugs, the validity of true strokes to this structure is not conclusive.

Summary

In summary, on the basis of the 150-meter weather tower installation which was properly instrumented and observed, we can detect no significant differences in strike frequency to the tower after the LEA installation than was noted before:- an average of 2 strike days per year. On this basis, we must conclude that the LEA array did not prevent strokes to the tower since strokes occurred on both the original and replacement arrays equally. On the question of whether the arrays affect the nature of the stroke or have some effect on what strokes do or do not strike, KSC is continuing to investigate; this latter question is more concerned with dissipation arrays as a concept than it is with LEA specifically.

HISTORY

June 21, 1971	-	How can we improve lightning protection of Apollo on pad? Various methods reported, dissipation arrays included.
1973	-	How can Shuttle be protected during rollout?
Nov. 15, 1973	-	Reviewed potential launch problems of ASTP. Resulting Instructions:- Investigate dissipation array concept for possible ASTP use.
May 21, 1974	-	Letter to KSC from JSC requested similar study.

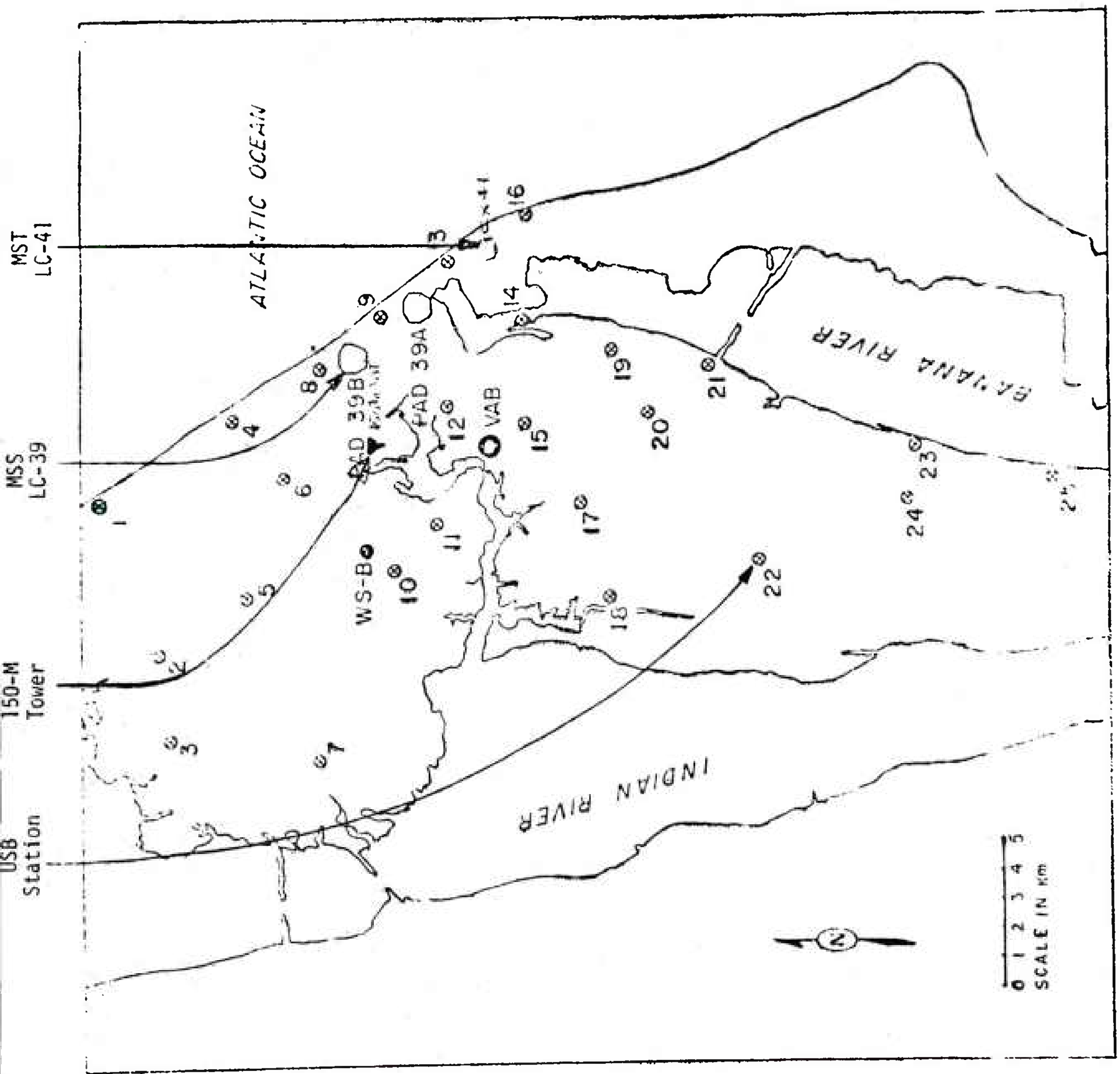
Dissipation arrays are installed at four locations:

150-Meter Weather Tower

Unified S-Band Station

Mobile Service Structure, LC-39

Mobile Service Tower, LC-41 (CCAFS)


ATLANTIC OCEAN
MST
LC-41
MSS
LC-39
150-M
Tower
USB
Station
PAD 39B
PAD 39A
VAB
WS-B
BANANA RIVER
INDIAN RIVER
N
0 1 2 3 4 5
SCALE IN km

150-METER WEATHER TOWER

Tower had nine year strike history going back to 1965; in that time (1965-1973), 18 strikes.

Three instrumented galvanized steel panels procured and installed on top of tower June 21, 1974, with temporary ground.

Tower struck June 22, 1974.

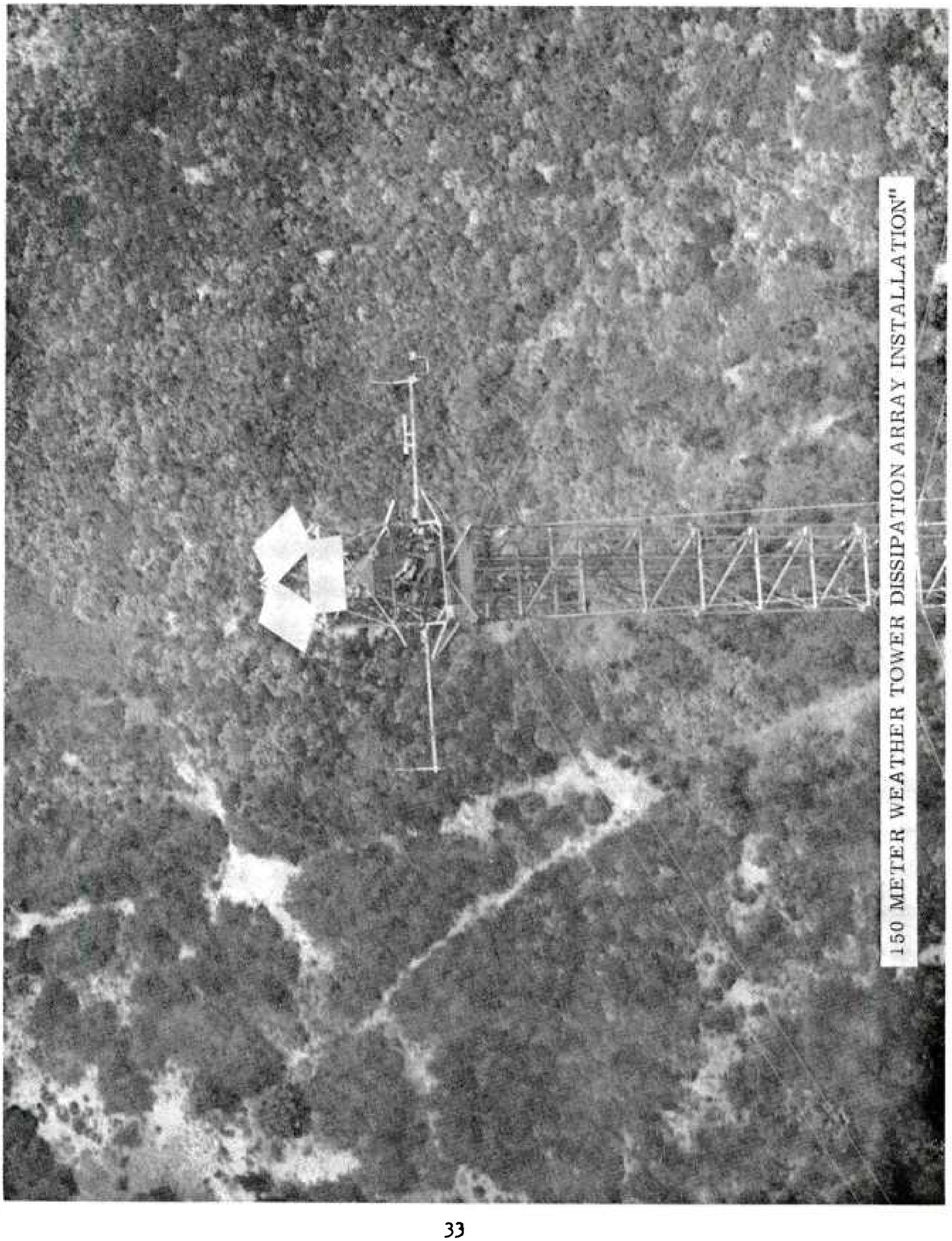
Grounding system of array completed June 30, 1974.

Report of defective panel manufacture received July 15, 1974. (Excessively thick galvanizing, blunting array points.)

Array struck twice July 18, 1974.

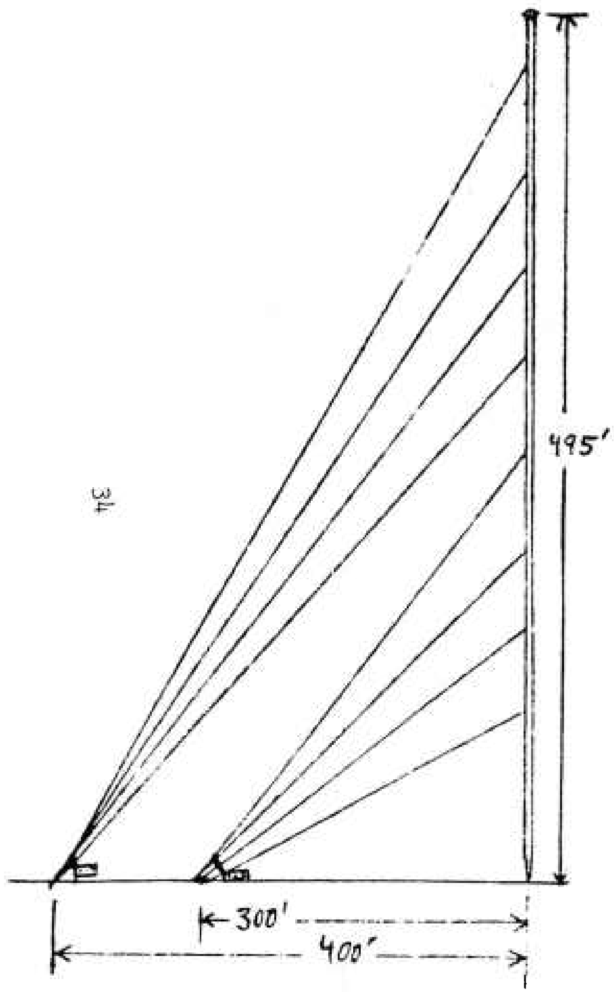
Galvanized panels replaced by stainless steel panels July 30, 1974.

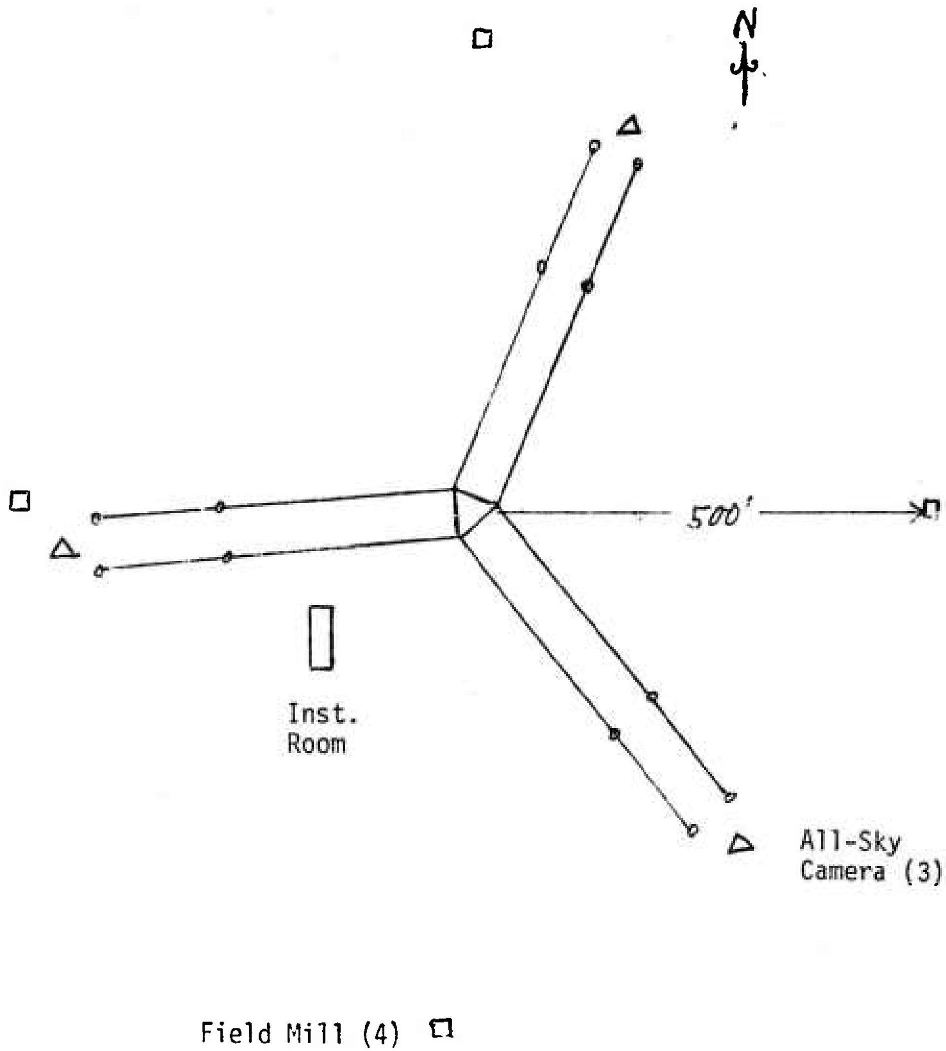
Array struck July 20, and October 3, 1975.



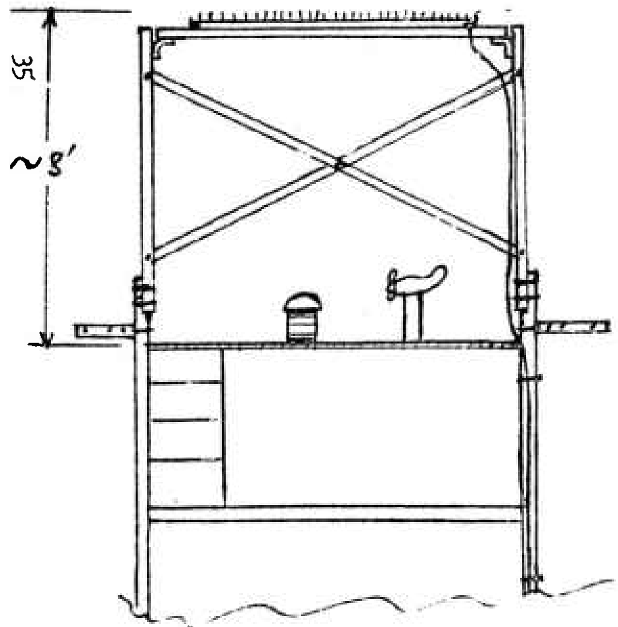
150 METER WEATHER TOWER DISSIPATION ARRAY INSTALLATION"

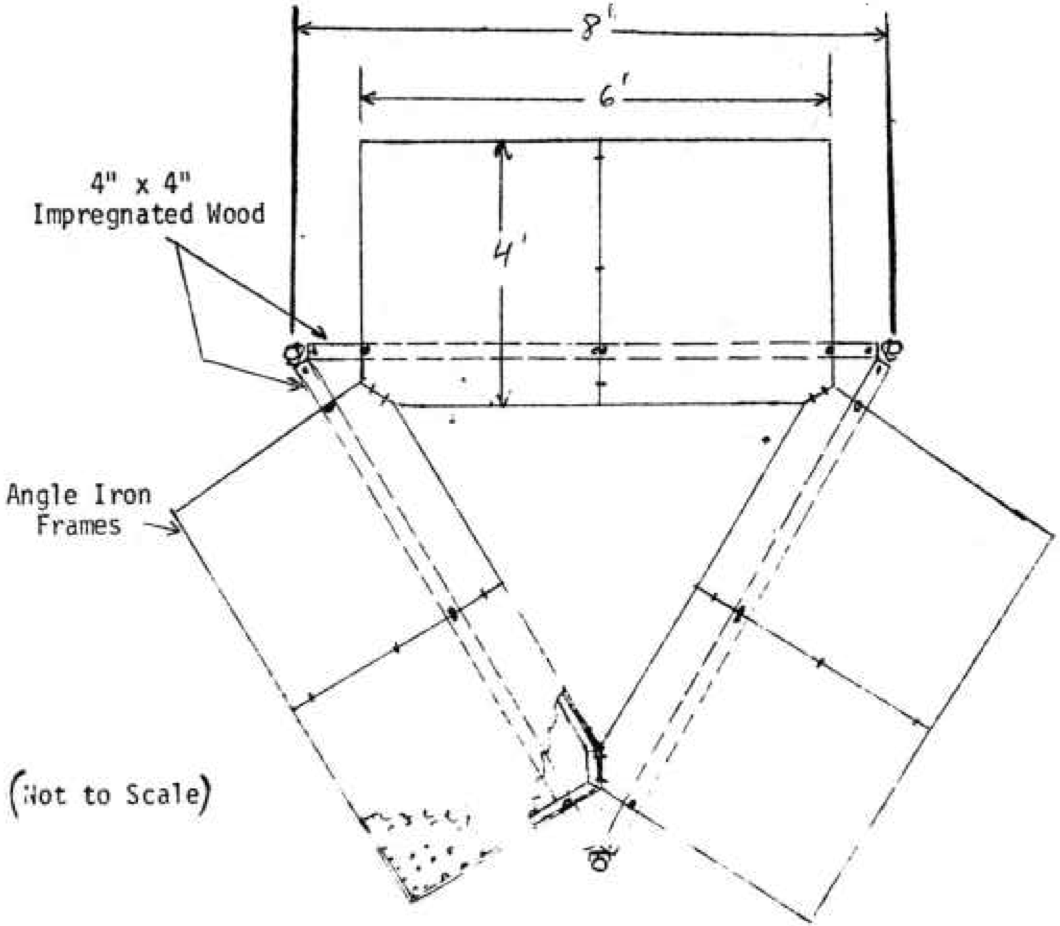
150 METER TOWER





150 METER TOWER ARRAY





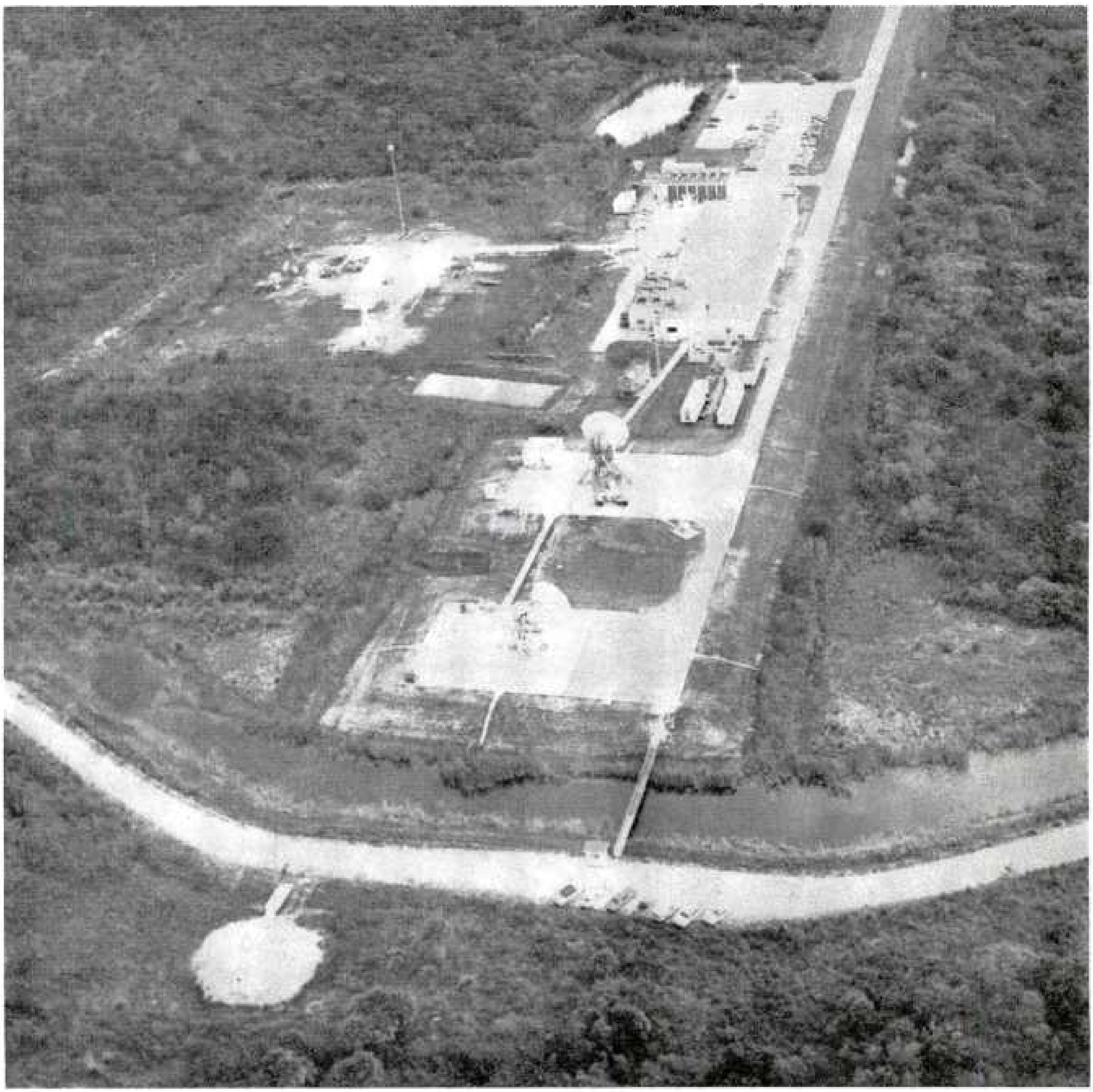
(Not to Scale)

UNIFIED S-BAND STATION

Installation made in June 1974 under auspices of Goddard Space Flight Center.

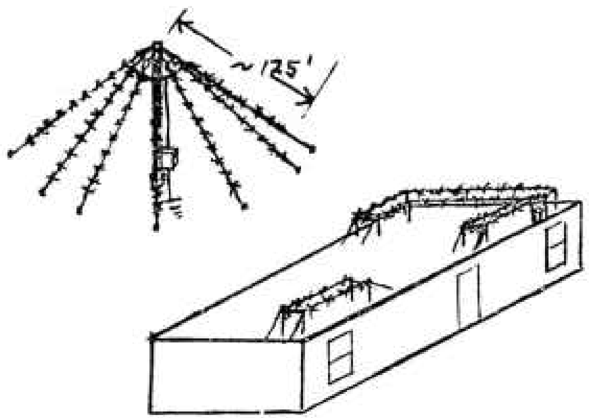
Four different instrumented dissipation array designs installed at four different locations.

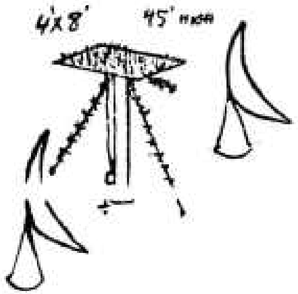
Unified S-Band Station has no history of being affected by lightning from commissioning (1966) to now.



UNIFIED S BAND TRACKING STATION

UNIFIED S-BAND STATION



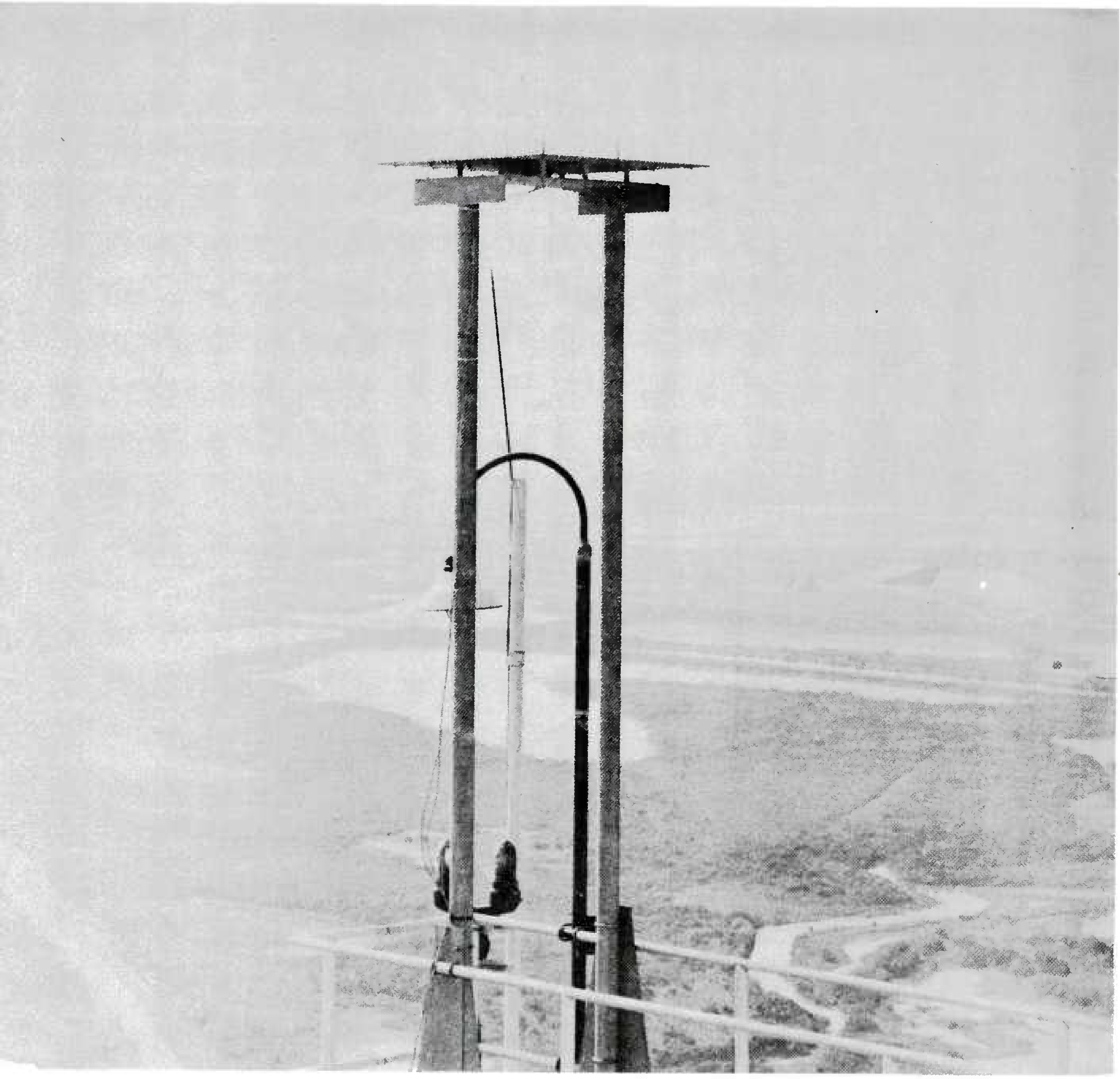


<u>MOBILE SERVICE STRUCTURE (MSS)</u>

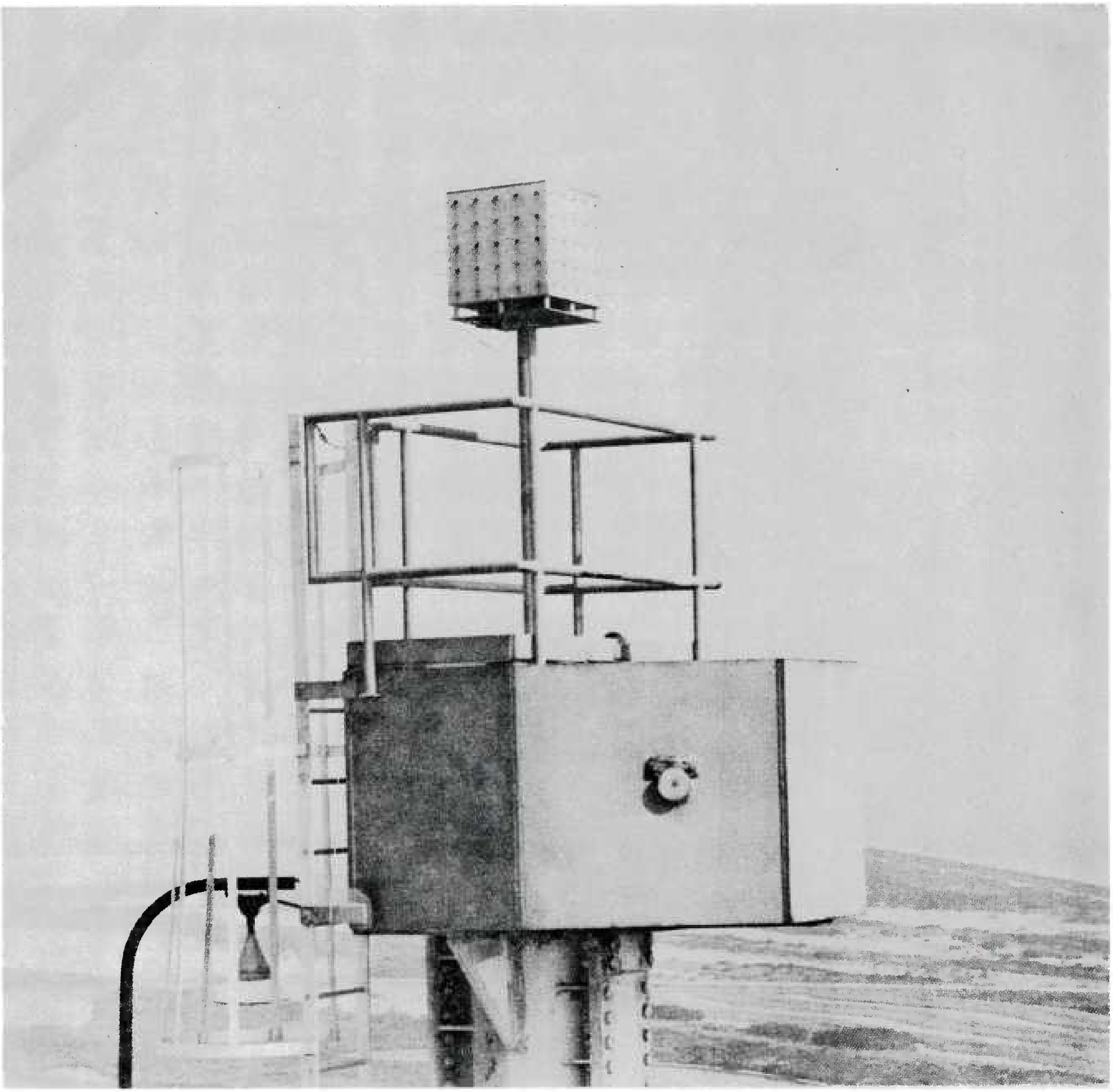
MSS strike record unknown before 1972 when lightning mast was installed. Strikes since then on 8/9/72, <u>5/24/73</u>, <u>6/17/73</u>, 7/29/73, 8/1/73, 5/5/74 and 5/12/74.

Four different instrumented array designs fabricated and installed in three locations on MSS. Installation completed 7/24/74.

MSS struck three times since then: - 7/25/74, 8/21/74, and <u>5/9/75</u>. All strikes went to mast. (Underlined strike dates occurred when MSS was on pad with LUT during launch operations. Others are strikes to MSS while standing free.)



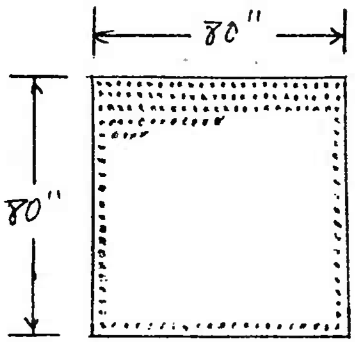
MOBILE SERVICE STRUCTURE, ARRAY #1



MOBILE SERVICE STRUCTURE, ARRAY #2

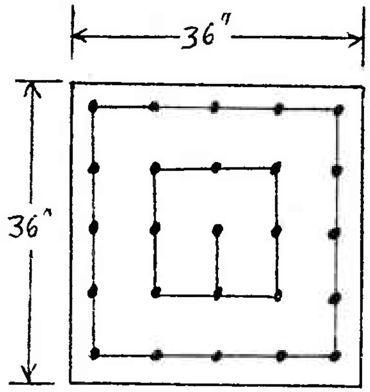
MOBILE SERVICE STRUCTURE, ARRAY #3

MSS ARRAYS



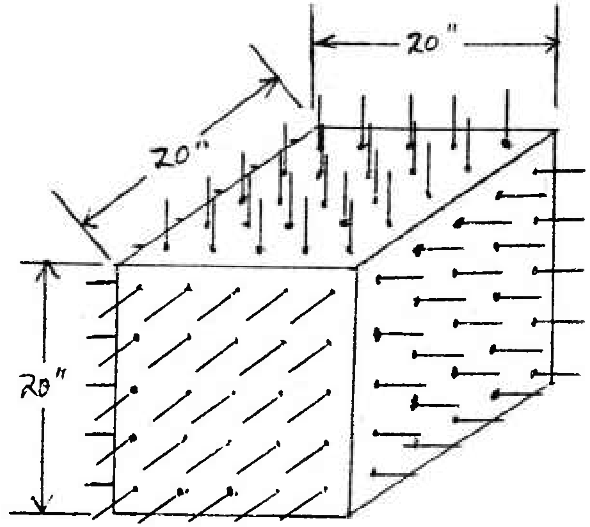
400 Point Array
Points 20 x 20 on 4" centers

ARRAY #3



25 Point Double Array
Points on 8" centers
Outer Ring 16 Points
Inner Set 9 Points

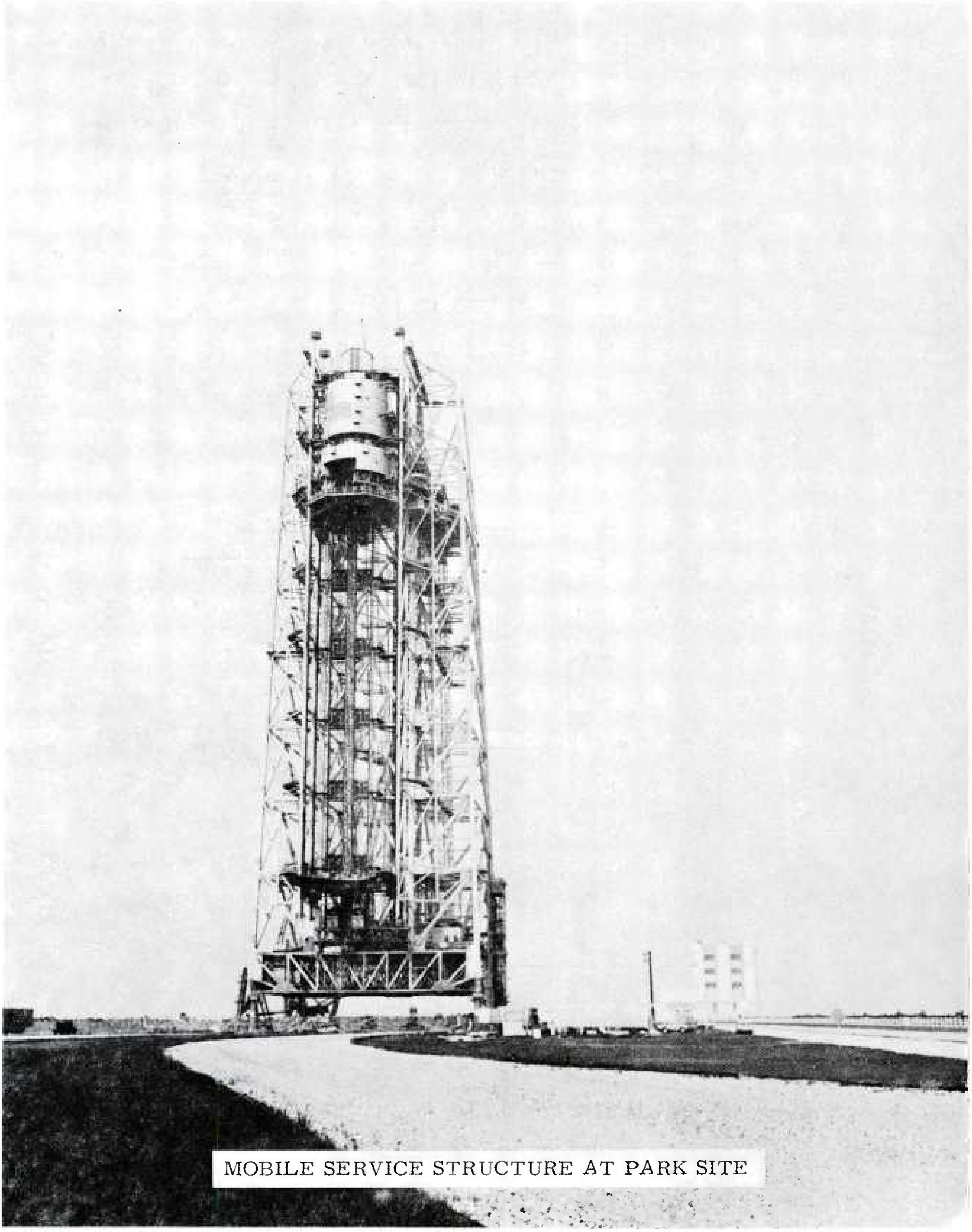
ARRAY #1



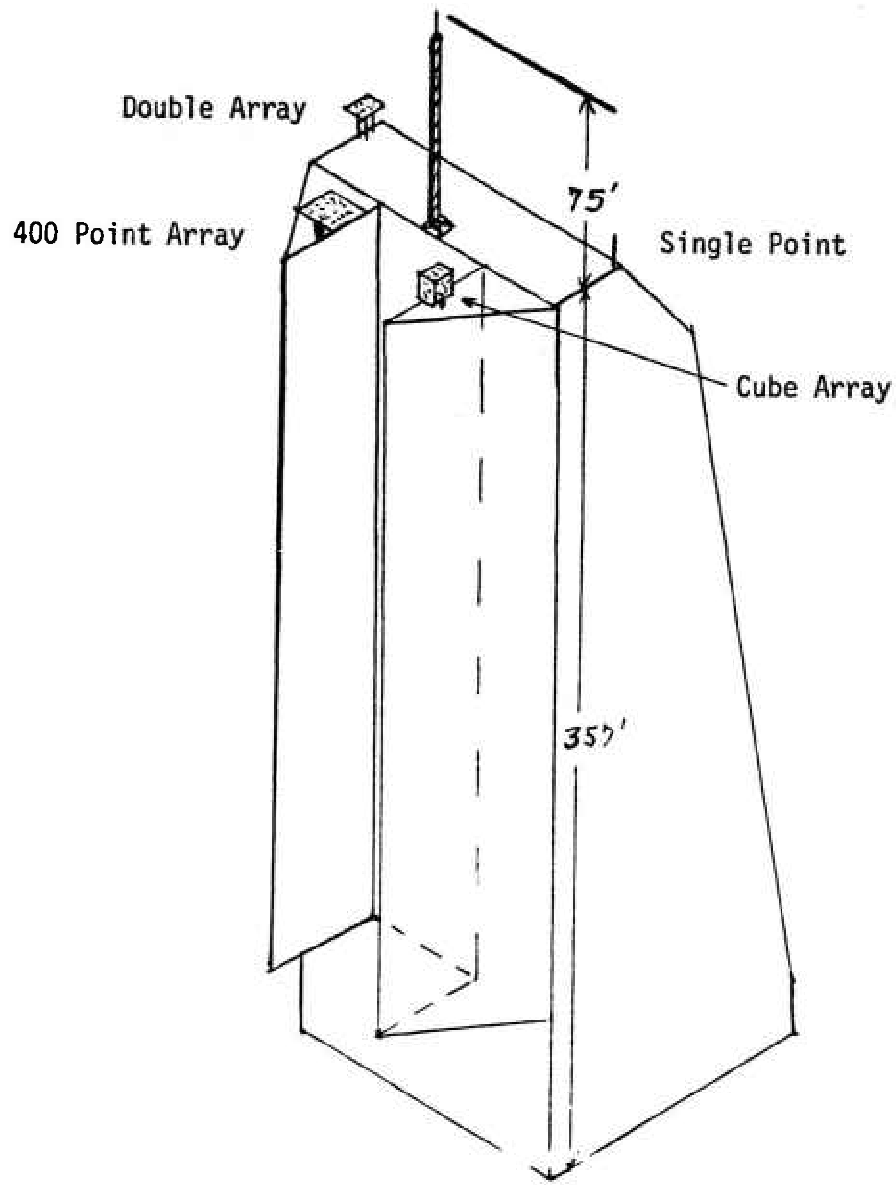
125 Point Cube Array
25 Points each 5 x 5
on 4" centers, top &
four sides

ARRAY #2

All Points 4" long stainless steel with tips $10^0 \pm 5^0$


MOBILE SERVICE STRUCTURE AT PARK SITE

MOBILE SERVICE STRUCTURE (MSS)



MOBILE SERVICE STRUCTURE, ARRAY #2
MOBILE LAUNCHER & INSULATED MAST

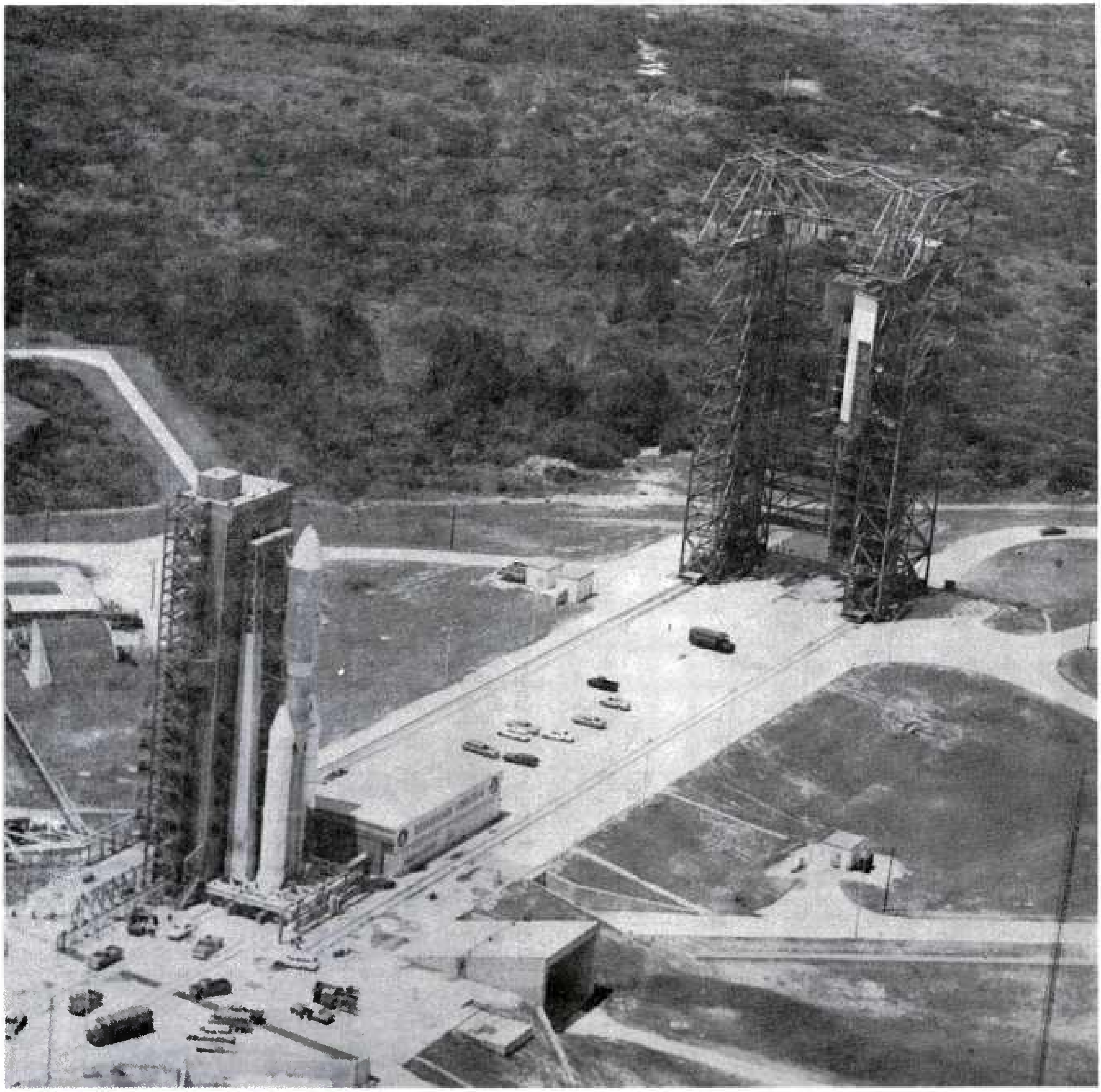
LC-41

Installation made under auspices of LeRC on request of LRC for Viking protection.

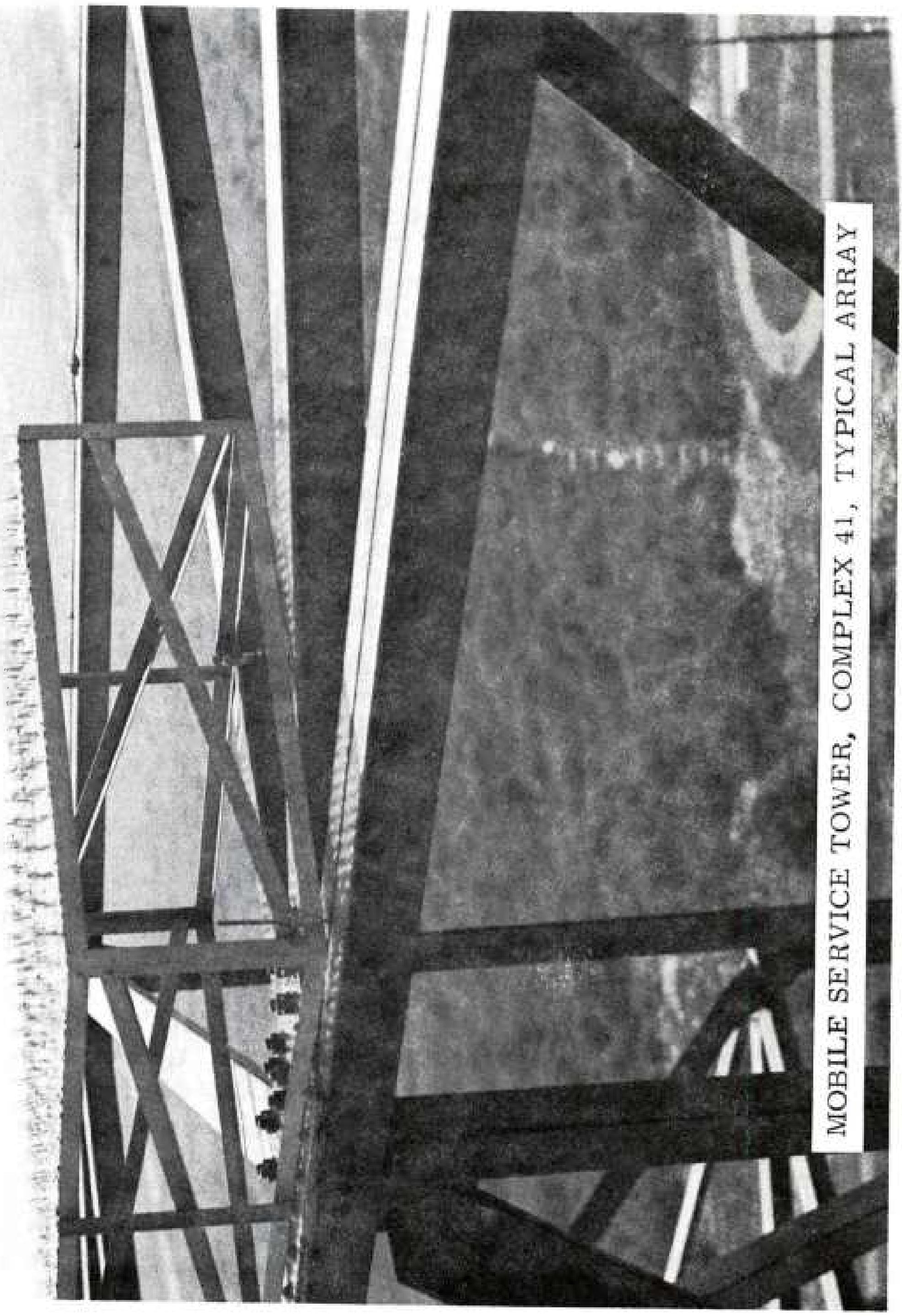
Ten stainless steel panels installed on Mobile Service Tower (MST) on 2/26/75. Panels were not instrumented and were welded in place in May 1975.

MST had structure instrumented to detect strokes 5/2/74. Four assumed strikes that year - 5/3, 6/11/ 6/22, and 7/22.

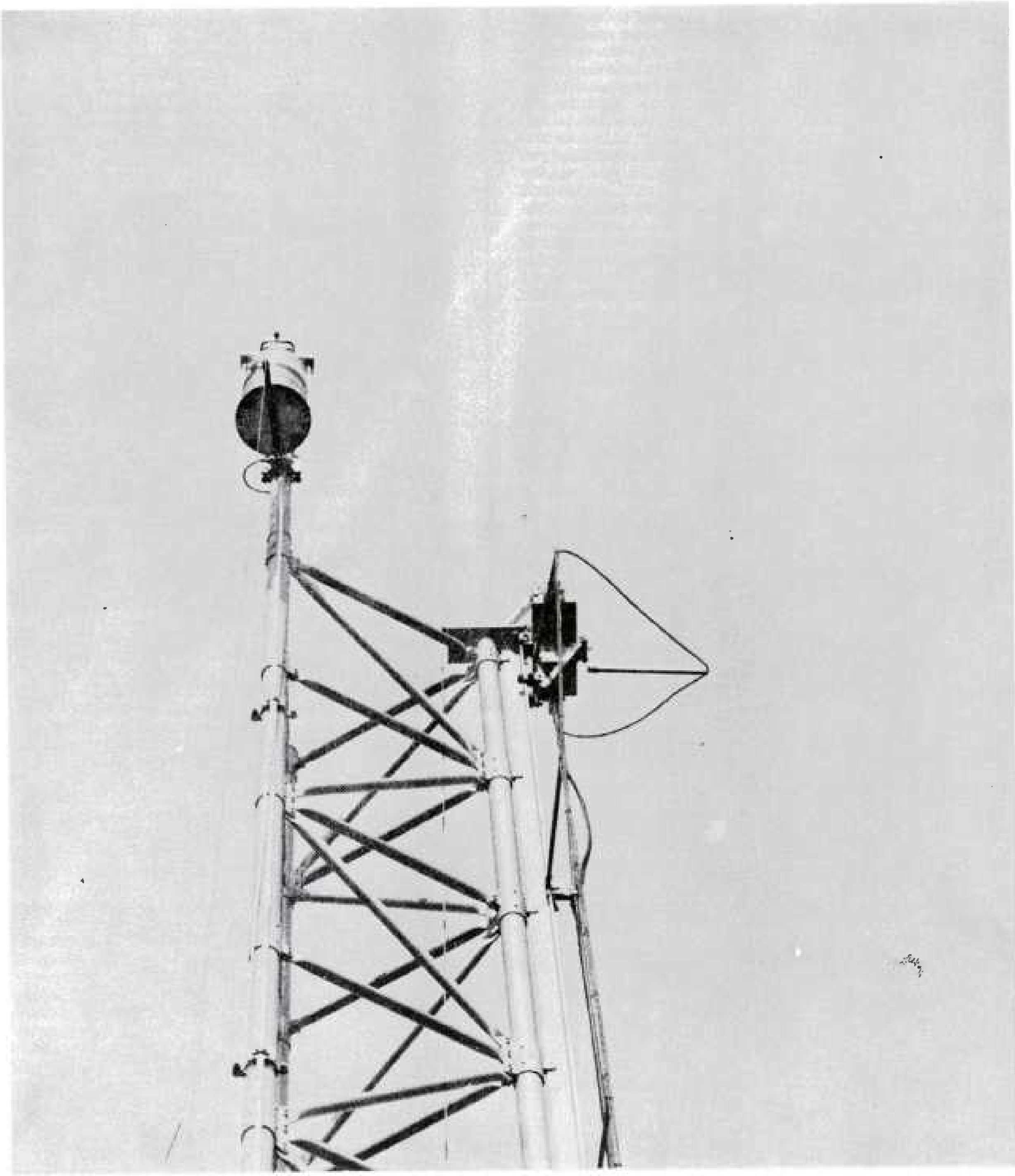
Two assumed strikes in 1975 - 6/7 and 6/16.



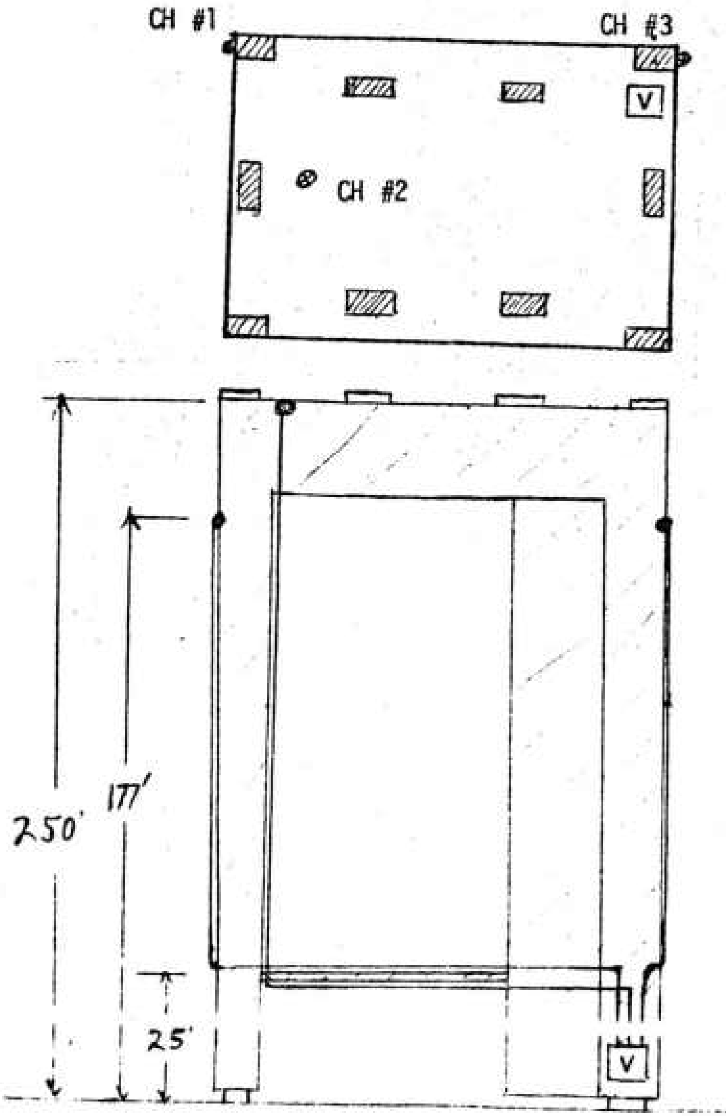
MOBILE SERVICE TOWER, COMPLEX 4-1



MOBILE SERVICE TOWER, COMPLEX 41, TYPICAL ARRAY



MOBILE SERVICE STRUCTURE LIGHTNING MAST INSTRUMENTATION



Each panel 4 x 6'.
Panels and points stainless steel.

Structure voltage leads of coax. Center conductor leads from structure to peak reading voltmeters at base. Shields float at top and grounded to base at bottom. Tower ground through RR wheels.

SUMMARY

In the short (2 year) period that we have had samples erected and under observation, dissipation arrays do not appear to have had any significant effect on the frequency of lightning strokes to tall structures at the Kennedy Space Center.

Effects on the nature of the strokes is still under study.

LIGHTNING ELIMINATION ASSOCIATES (LEA) ARRAY ON TOP OF 150 METER TOWER AT KSC

by

Welby T. Risler

of

NASA/Kennedy Space Center,
Florida 32815

November 6, 1975

SUBJECT: Lightning Elimination Associates (LEA) Array on Top of 150-Meter Tower at KSC

The LEA array was instrumented to evaluate its performance and to determine what physics principles were involved in its operation. An early review of records eliminated the discharging of clouds as a means of lightning protection. The charging rate in the storm clouds were orders of magnitude greater than the discharging rate of the LEA array. The nominal value of the LEA discharge current during storms was approximately 150 microamperes. E. T. Pierce gives 10 to 30 coulombs as the nominal charge transferred to ground from a lightning strike. It would take 18.5 hours for the LEA array to release 10 coulombs of charge at a rate of 150 microamperes. The clouds overhead were able to regenerate electric fields back to their original value within one to four minutes after a flash. Any success for this array to ward off lightning strikes would have to be caused by a local condition at the tower.

Consideration was given to the space charge produced at the array. Figure 1 is an illustration of a negatively charged cloud inducing positive charges at the array points. The field lines emanating from the cloud converge at the array points to produce electric fields high enough to cause current to flow into the air. This space charge in the air terminates some of the field lines causing the array points to be shielded from the cloud. It should be stated that the triangular weather tower had a pointed lightning rod at each corner before the array was installed. We are therefore comparing a 3-pointed configuration with a many-pointed configuration. The spacing between points and height is important. The total number of field lines is determined by the charge magnitude in the cloud. Therefore, for a given array area, the field lines have to be shared between the points. Increasing the number of points for an area can reduce the discharge current. The space charge does have properties which could influence lightning results. Space charge over the array will electrically shield the array. This would make it more difficult for an approaching lightning leader to initiate a leader from the array. Also, electrical shielding would make the tower look electrically more flat to the storm cloud. Space charge which has drifted up and away from the array, could deflect lightning either toward or away from the tower. The torturous path of lightning is believed (M. Uman) to be caused by charges or ions in the neighborhood of the step leader. The space charge has the opposite sign (see Figure 1) of an approaching leader. This could retard or extinguish weak leaders or their branches.

Since the approved LEA array was struck on October 3, 1975, its evaluation now is how much it may improve the lightning environment. This necessitates a statistical approach. To help accomplish this, it was decided that it would be useful to detect the number of close strikes with leaders to the array. It is believed this can be done with the present methods of recording LEA discharge currents and electric fields at the tower. Figures 2, 3, and 4 are samples of LEA currents and electric fields recorded under three different lightning conditions.

Figure 2 depicts a distant strike having a number of return strokes lasting almost a second. Just before the strike, the electric field east of the tower was 7.5 KV/M negative and the LEA current was 150 microamps negative. Negative is defined as those fields and currents produced by a negative charge overhead. The LEA current value is obtaining by measuring the voltage developed across a parallel resistance and capitance. The time constant of resistor and capacitor is approximately 5 milliseconds. It is believed that the currents recorded are those produced by LEA discharges and are not displacement currents. The large long period excursion in the positive direction of LEA current is due to the positive space charges existing after the strike. The space charge electric fields are now free to attach themselves to the LEA array instead of the clouds.

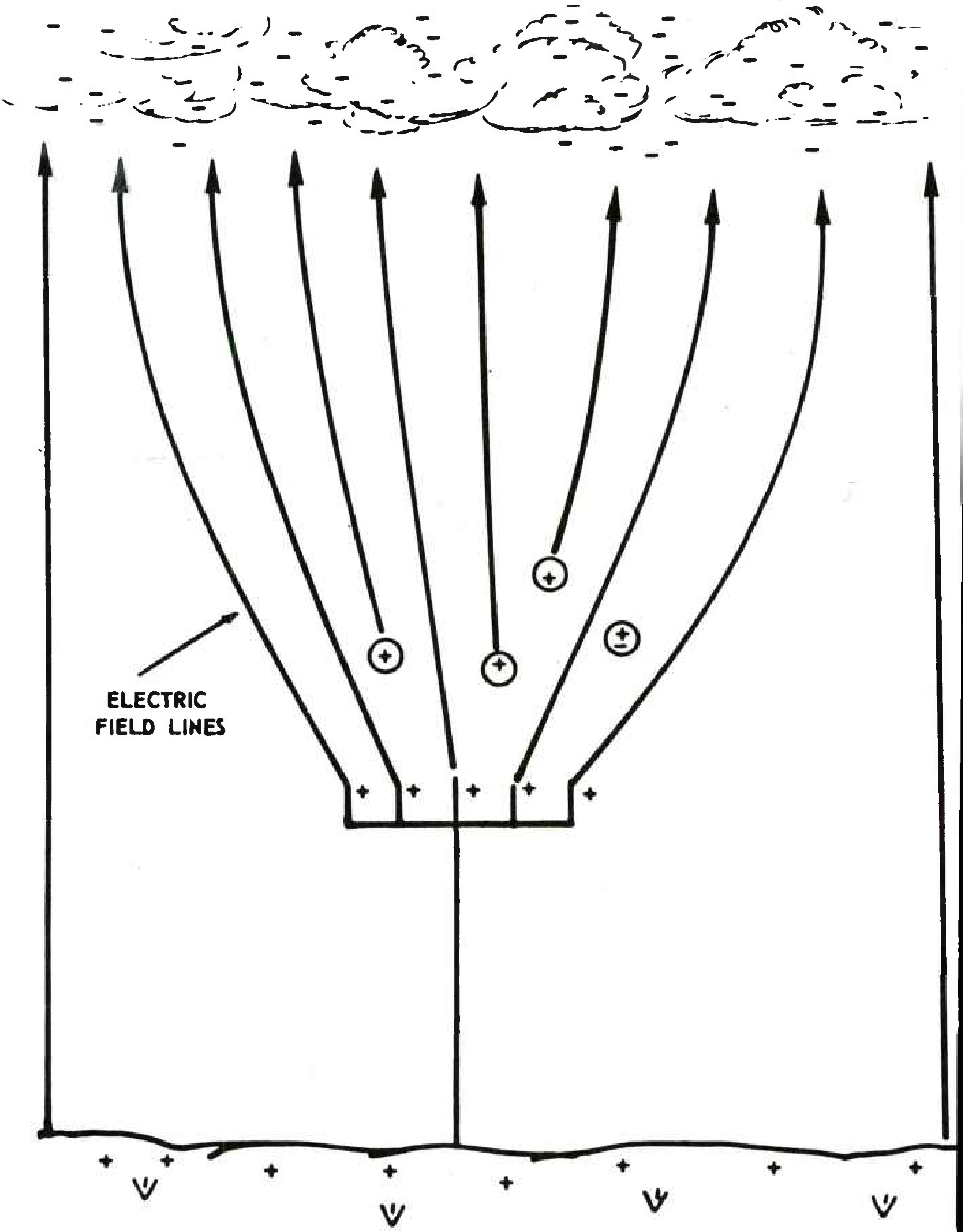
In Figure 3, the fields and LEA current are believed due to a close by strike. A close by strike is one in which positively charged corona is induced in an already existing positive space charge. In Figure 3, a corona current spike due to the negatively charged leader appears before the current reversal due to the released space charge acting in consort with the small positive field of the cloud after the strike. An integrated bump exists in the field measurement before the strike due to integration by a low pass filter in the instrument unit.

Figure 4 are fields and current believed due to a nearby weak leader that became extinguished. A corona streamer is emitted in the LEA current record but there is little change in measurement of the electric field. This indicates a leader not followed by a strike. There is only an integrated small bump superimposed on the slowly charging negative field. There is not a subsequent reversal in LEA current. It is to be mentioned that there were few occasions where this was observed.

Figure 5 are video tape photos of two strikes to the tower on July 18, 1974. The wind was moving toward the storm. The space charge would therefore move up and toward the storm providing a possible breakdown path for a leader. The strike on October 3, 1975, also had a surface wind from the North while the storm moved in from the south. Where surface winds are blowing toward clouds, space charge may deflect lightning toward a tower.

Figure 6 are the fields and LEA current taken during one of the strikes of July 18, 1974. The records show two strikes 0.5 seconds apart. The second strike disabled the field measuring instruments. It is deduced that the leader from the first strike pulled off a negative current (positive space charge) streamer. This was followed by a current reversal which indicates the strike did not make contact with the LEA array. The second strike did make contact and resulted in mostly all negative current.

The statistical evaluation of the LEA array would require periods of observation with the LEA in the grounded and ungrounded configuration. The ungrounded configuration should give us very little space charge and therefore should tell us what influence the space charge may have.


ELECTRIC
FIELD LINES

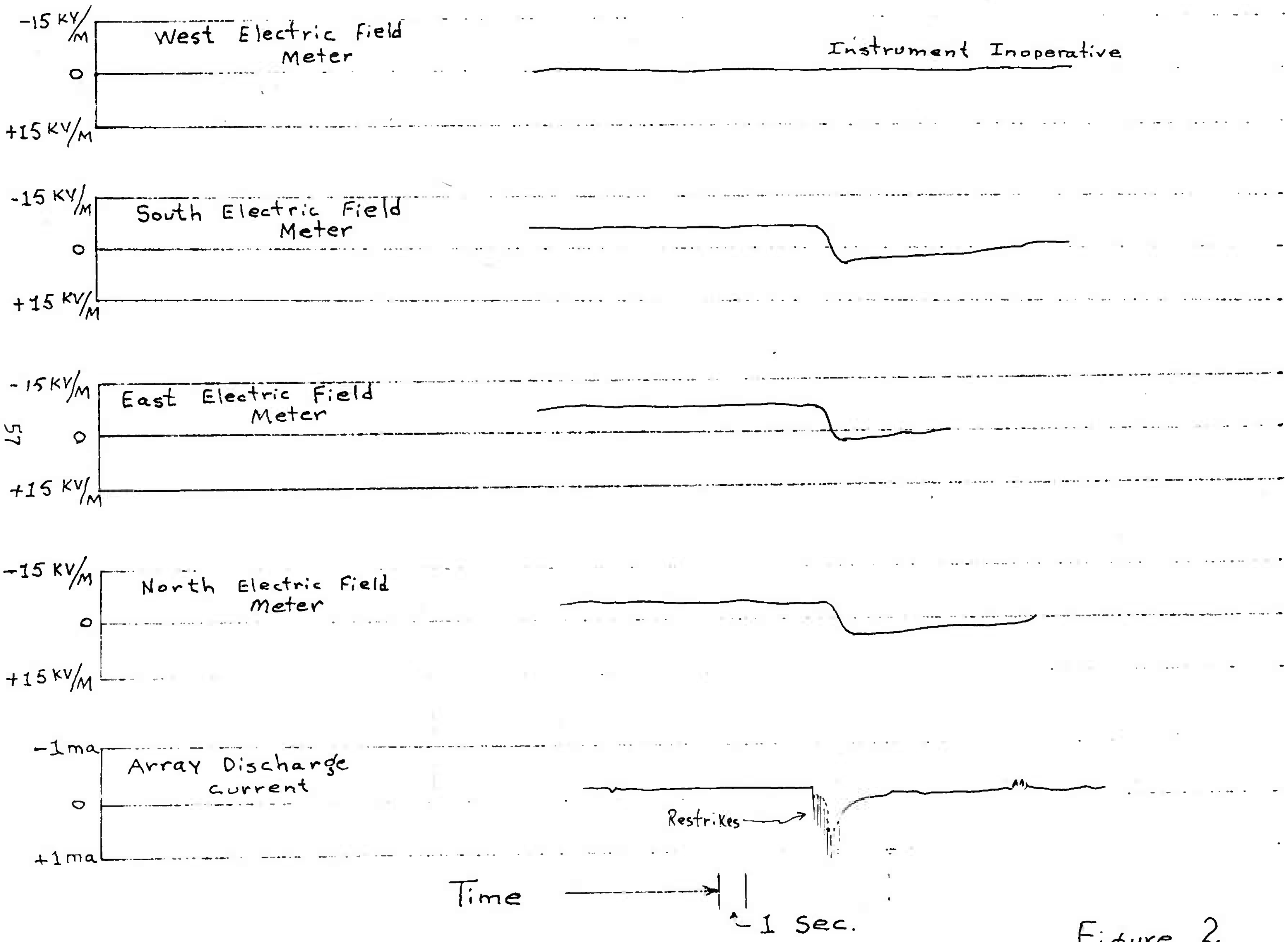

-15 KV/M
0
+15 KV/M
West Electric Field Meter
Instrument Inoperative
-15 KV/M
0
+15 KV/M
South Electric Field Meter
-15 KV/M
0
+15 KV/M
East Electric Field Meter
-15 KV/M
0
+15 KV/M
North Electric Field Meter
-1 ma
0
+1 ma
Array Discharge current
Restrikes
Time
~1 Sec.

Figure 2.

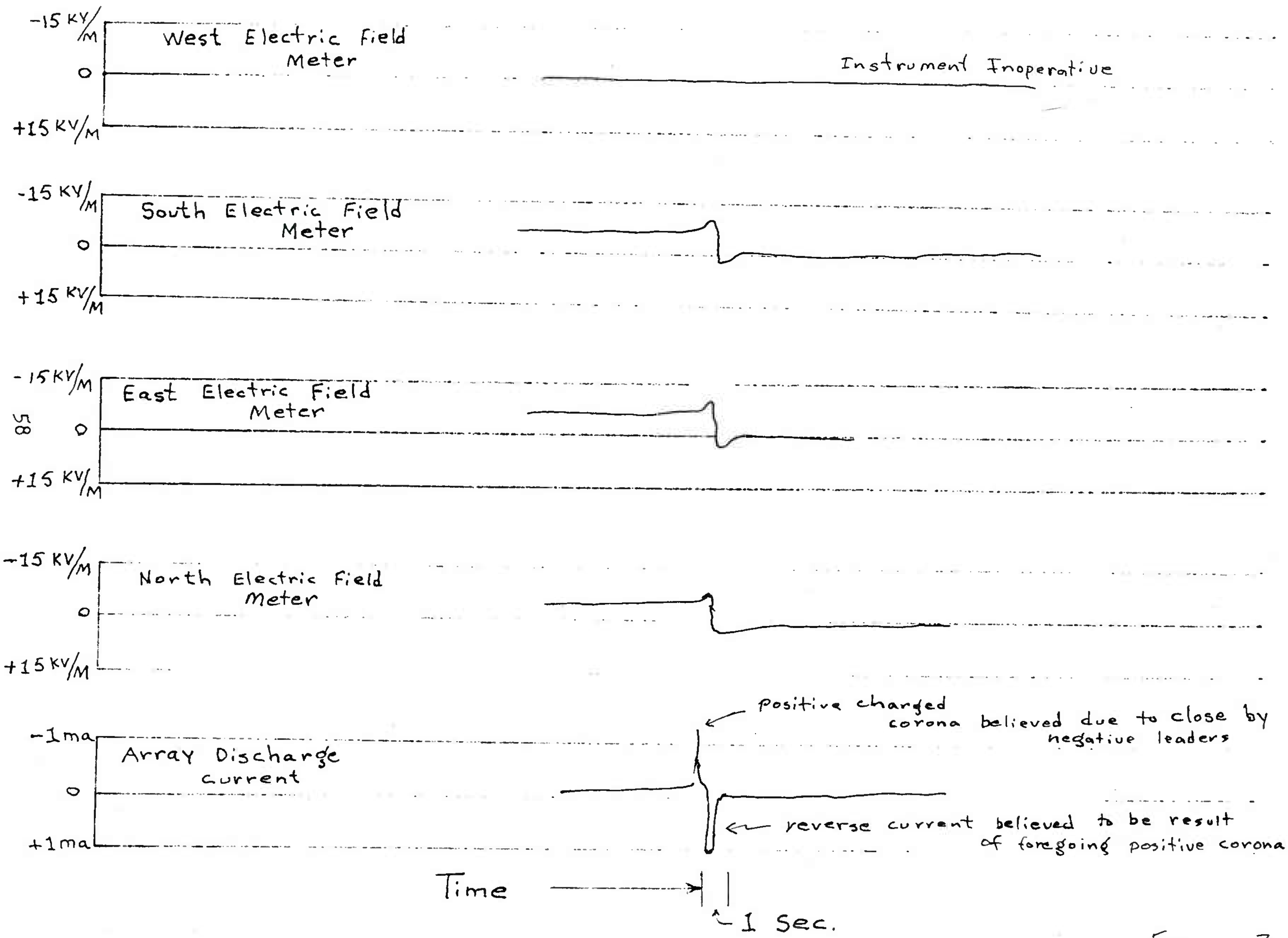
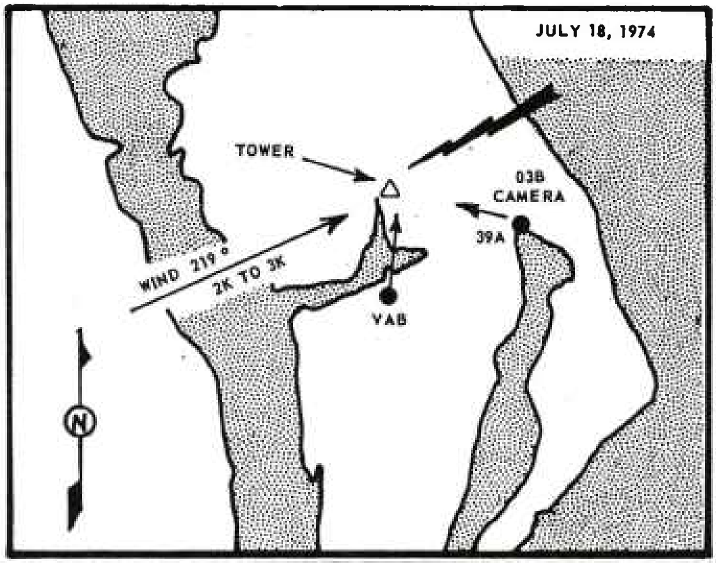
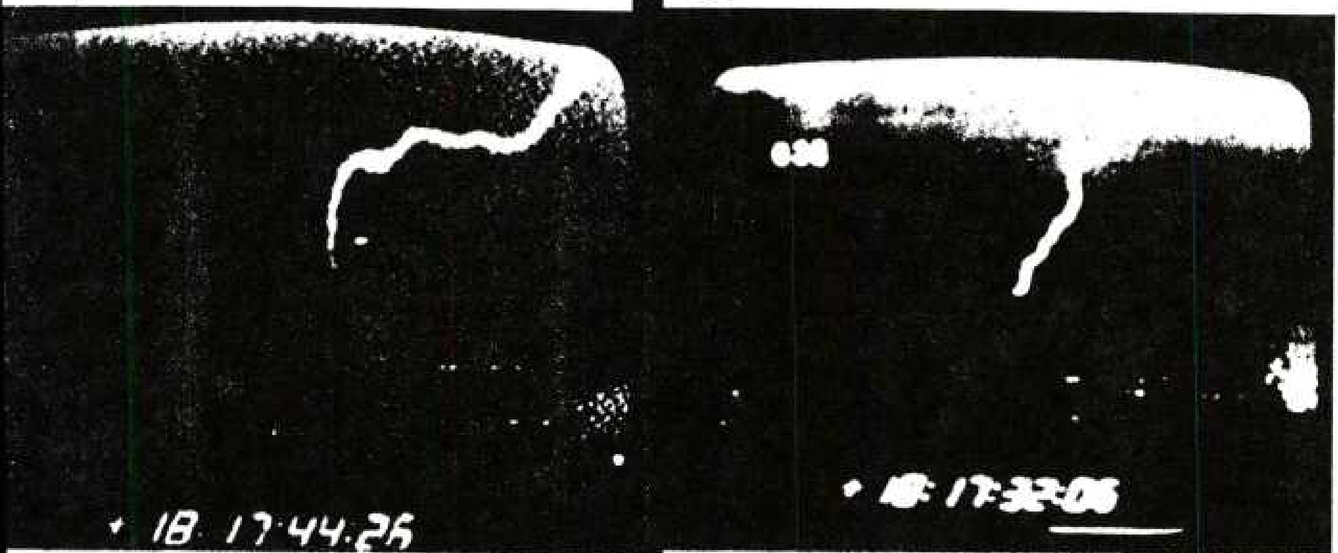

-15 KV/M
0
+15 KV/M
West Electric Field Meter
Instrument Inoperative
South Electric Field Meter
East Electric Field Meter
North Electric Field Meter
-1 ma
+1 ma
Array Discharge current
positive charged corona believed due to close by negative leaders
reverse current believed to be result of foregoing positive corona
Time
1 Sec.

Figure 3



JULY 18, 1974
TOWER
03B
CAMERA
39A
WIND 219°
2K TO 3K
VAB
N

-2



18 17 44 26

1 —

06

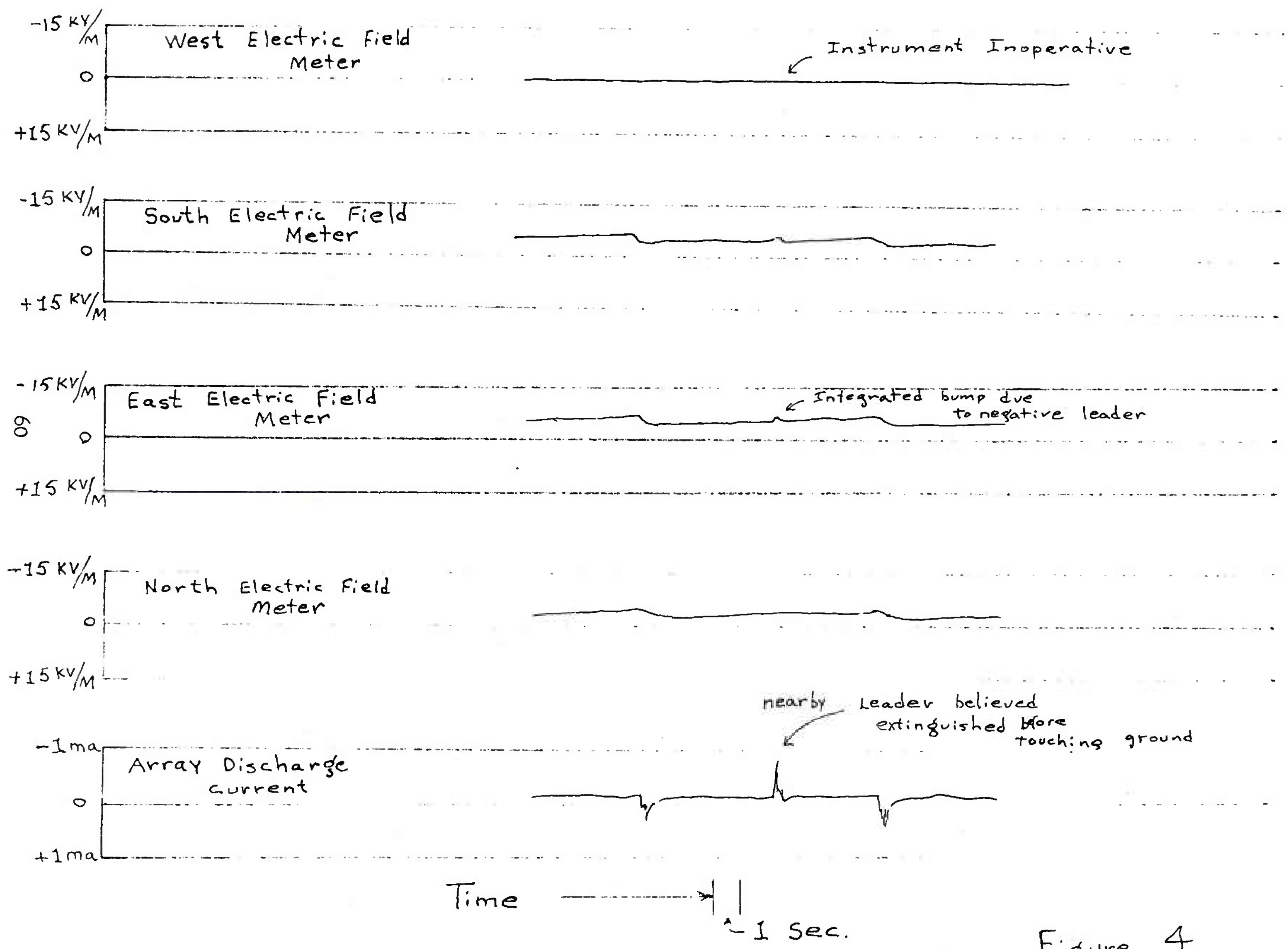
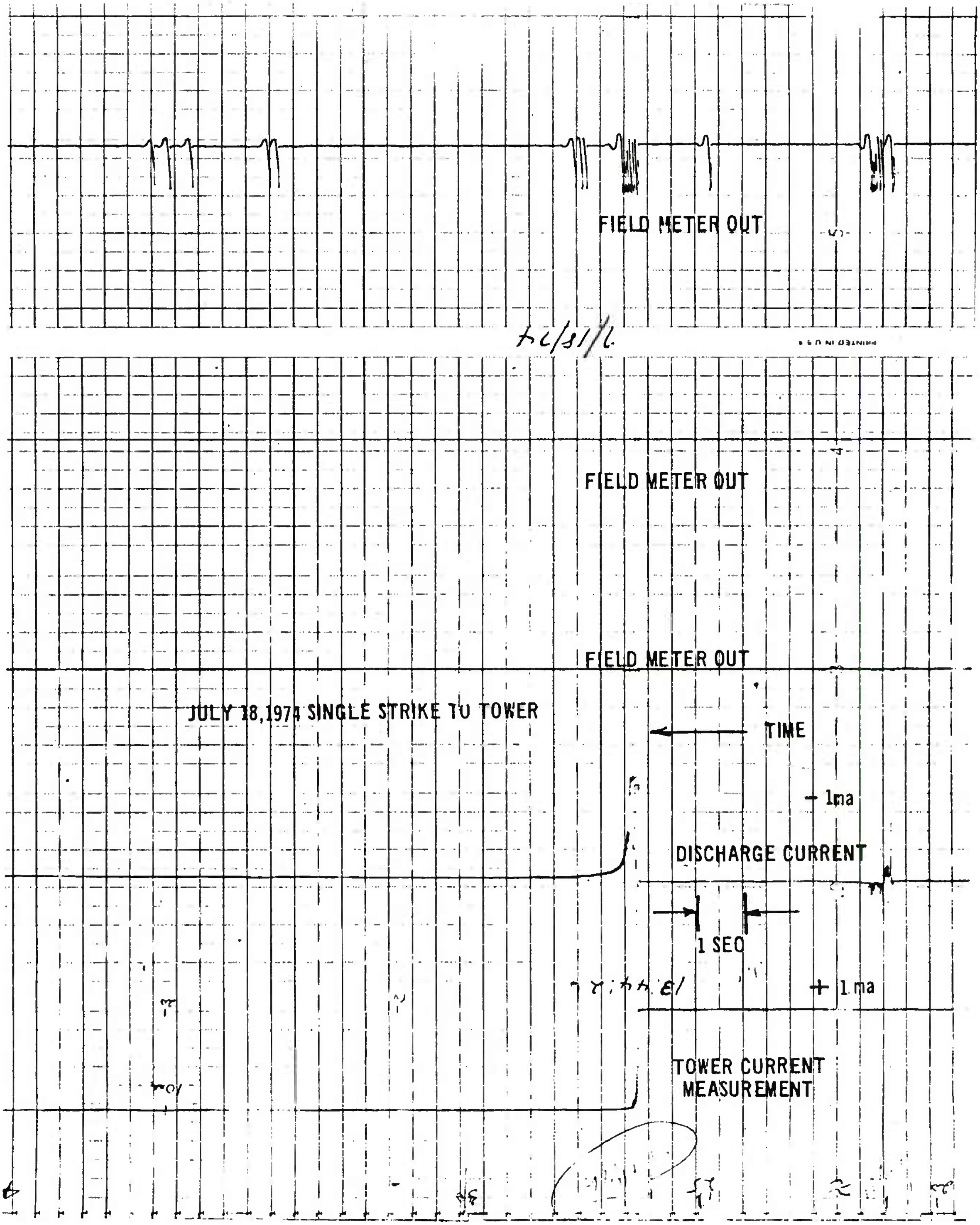
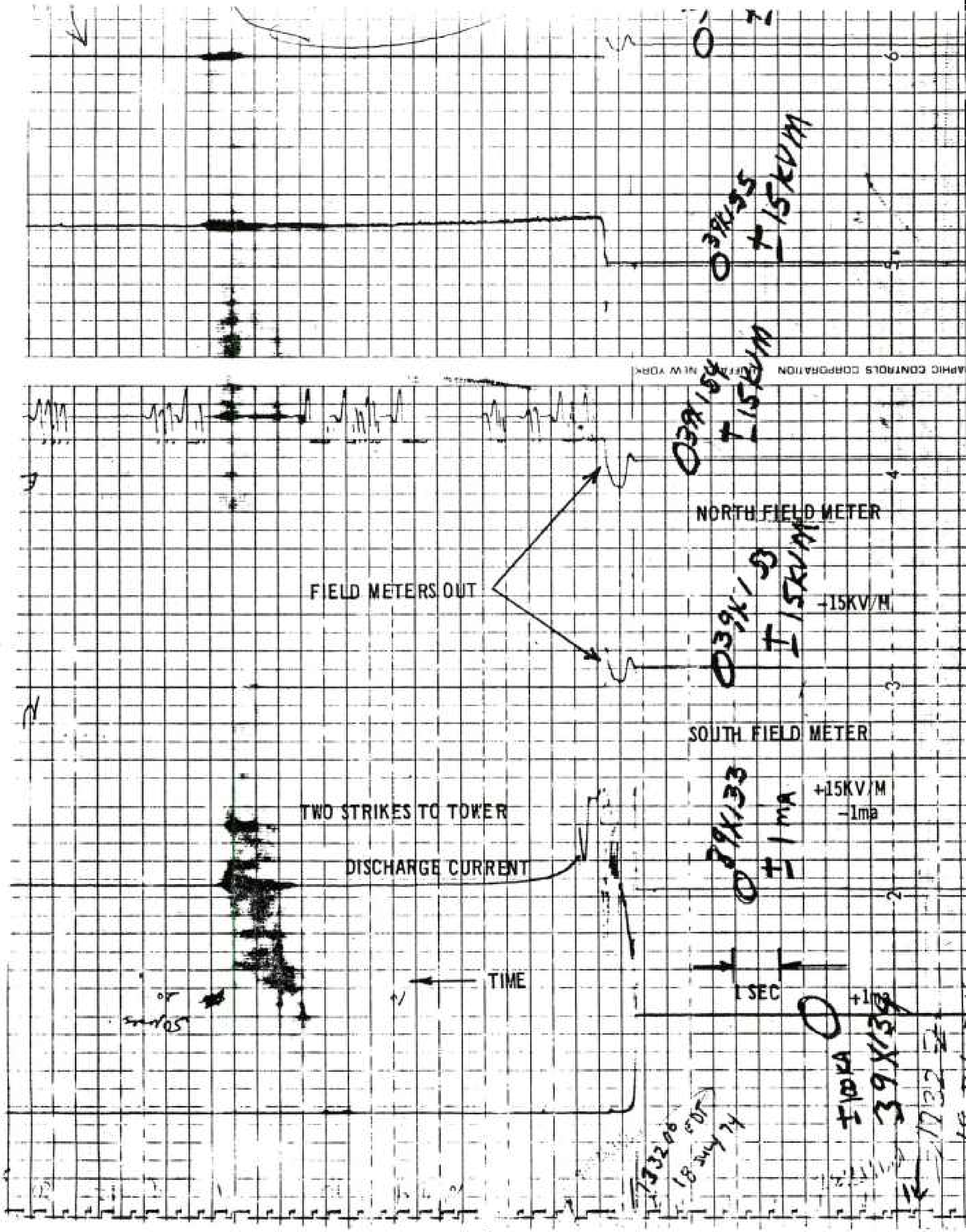

-15 KV/M
0
+15 KV/M
West Electric Field Meter
Instrument Inoperative
-15 KV/M
0
+15 KV/M
South Electric Field Meter
-15 KV/M
0
+15 KV/M
East Electric Field Meter
Integrated bump due to negative leader
-15 KV/M
0
+15 KV/M
North Electric Field Meter
-1 ma
0
+1 ma
Array Discharge current
nearby Leader believed extinguished before touching ground
Time
~1 Sec.

Figure 4


FIELD METER OUT
FIELD METER OUT
FIELD METER OUT
JULY 18,1974 SINGLE STRIKE TO TOWER
TIME
1ma
DISCHARGE CURRENT
1 SEC
1 ma
TOWER CURRENT MEASUREMENT


NORTH FIELD METER
FIELD METERS OUT
+15KV/M
SOUTH FIELD METER
+15KV/M
-1ma
TWO STRIKES TO TOWER
DISCHARGE CURRENT
TIME
1 SEC
+1ma

SUMMARY

1. NEARBY LIGHTNING STRIKES AND LEADERS CAN BE DETECTED BY THE PRESENT INSTRUMENTS AT THE WEATHER TOWER.

2. THERE WERE OCCASIONS OF NEARBY LEADERS NOT MAKING CONTACT WITH THE GROUND.

3. SPACE CHARGE DOES CONSIDERABLE ELECTRICAL SHIELDING OF THE ARRAY AS INDICATED BY THE RELATIVELY LARGE CURRENT REVERSALS WITH SUDDEN REDUCTIONS IN ELECTRIC FIELDS.

4. THE RATE OF CHARGE SEPARATION WITHIN CLOUDS IS TO RAPID FOR THE WEATHER TOWER ARRAY TO DISCHARGE NEARBY CELLS.

FOURTH KSC PRESENTATION
AT JSC HOUSTON

Paper given

by

J. R. Stahmann

of

NASA/Kennedy Space Center,
Florida 32815

November 6, 1975

FOURTH KSC PRESENTATION AT JSC HOUSTON
November 6, 1975

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P.O. Box 21266
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(305) 867-3407

At Bicentennial time for the United States, the idea of eliminating lightning by silently dissipating the charges in a thunderstorm using a number of points on structures celebrates its 225th anniversary, dating back to Ben Franklin's time (slide 1).

A study of the energy in a moderate thunderstorm reveals very large energies and a charge separation current of several amperes (slide 2). The discharge currents from foliage and structures do not dissipate a storm so that any dissipator to be noticeably effective must augment such currents by a much higher current of at least 10% that of the storm or several hundred milliamperes. Instead, dissipation arrays produce only several hundred microamperes, 1/10,000 of the thunderstorm charging current. Moreover, measured quasi-steady state dissipation current maximums are reached usually at the end of storms (slide 3) or even in the winter (slide 4). During the height of the storm the current is usually low.

KSC has installed several unique arrays on the MSS structure as described earlier by Bill Durrett. A 400-point array with points 4 inches apart produced currents in excess of 500 microamperes (slide 5). The nine points on the inside of a 25-point array, with points 8 inches apart, produced 450 microamperes or 50 microamperes per point (slide 5). The weather tower LEA array produced a maximum of only 0.2 microamperes per point. A single separate corona point produced maximum currents of the order of 50 microamperes. The time of peak current was a function of array location relative to the charged cloud regions (slide 6)

The pulse response of the arrays to field collapses (slide 7) shows a larger response for the outer points of the 25-point array. A stroke at 2201 EDT on May 9, 1975, reportedly hit the MSS. A negative field collapse on nearby field mills indicates a positive stroke polarity. Positive strokes to ground tend to occur near the end of a storm with a long interval between strokes (slide 8). Strokes to moderate-height towers about 500 feet high, typical of KSC tower heights, have been reported near the end of storms. There is some evidence that space charge over structures of moderate height could favor positive strokes at the expense of negative strokes. Since the rates of rise of current of positive strokes are much less than those of negative strokes, the threat of magnetically induced voltages in the structure is minimized.

IN 1750

MR. EDWARD CARE
(a publisher of Franklin's papers)
said in part:

"THERE SHOULD BE PUT A ROD OF IRON 8 TO 10 FEET IN LENGTH, SHARPEN'D GRADUALLY TO A POINT LIKE A NEEDLE, AND GILT TO PREVENT RUSTING, OR DIVIDED INTO A <u>NUMBER OF POINTS</u> WHICH WOULD BE BETTER--THE ELECTRICAL FIRE WOULD, I THINK, BE DRAWN OUT OF THE CLOUD SILENTLY, BEFORE IT COULD COME NEAR ENOUGH TO STRIKE."

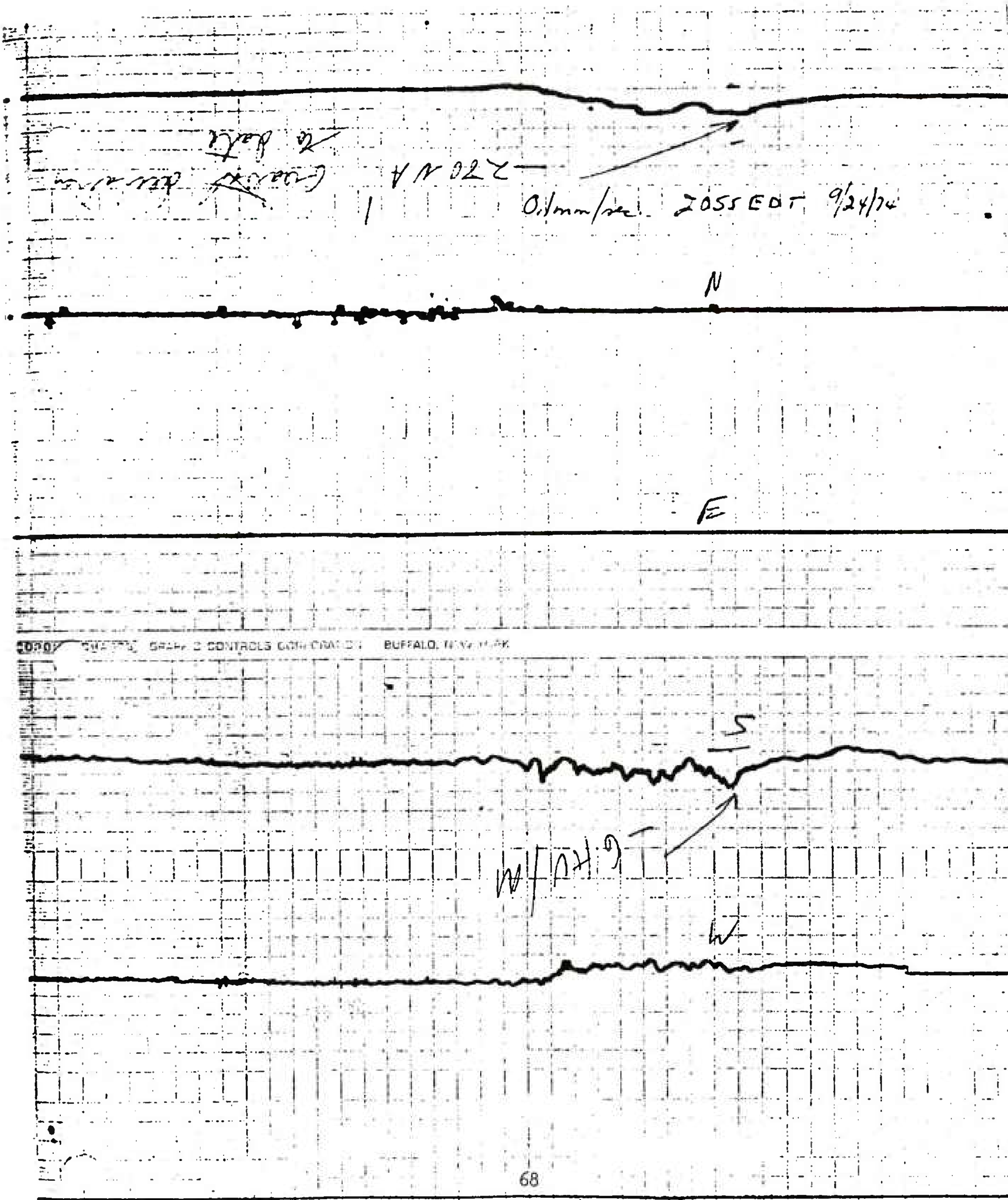
J.R. Stahmann/PRC-1210/KSC

Slide 1.

FROM: ENERGY GENERATION IN A THUNDERSTORM - G.D.FREIER

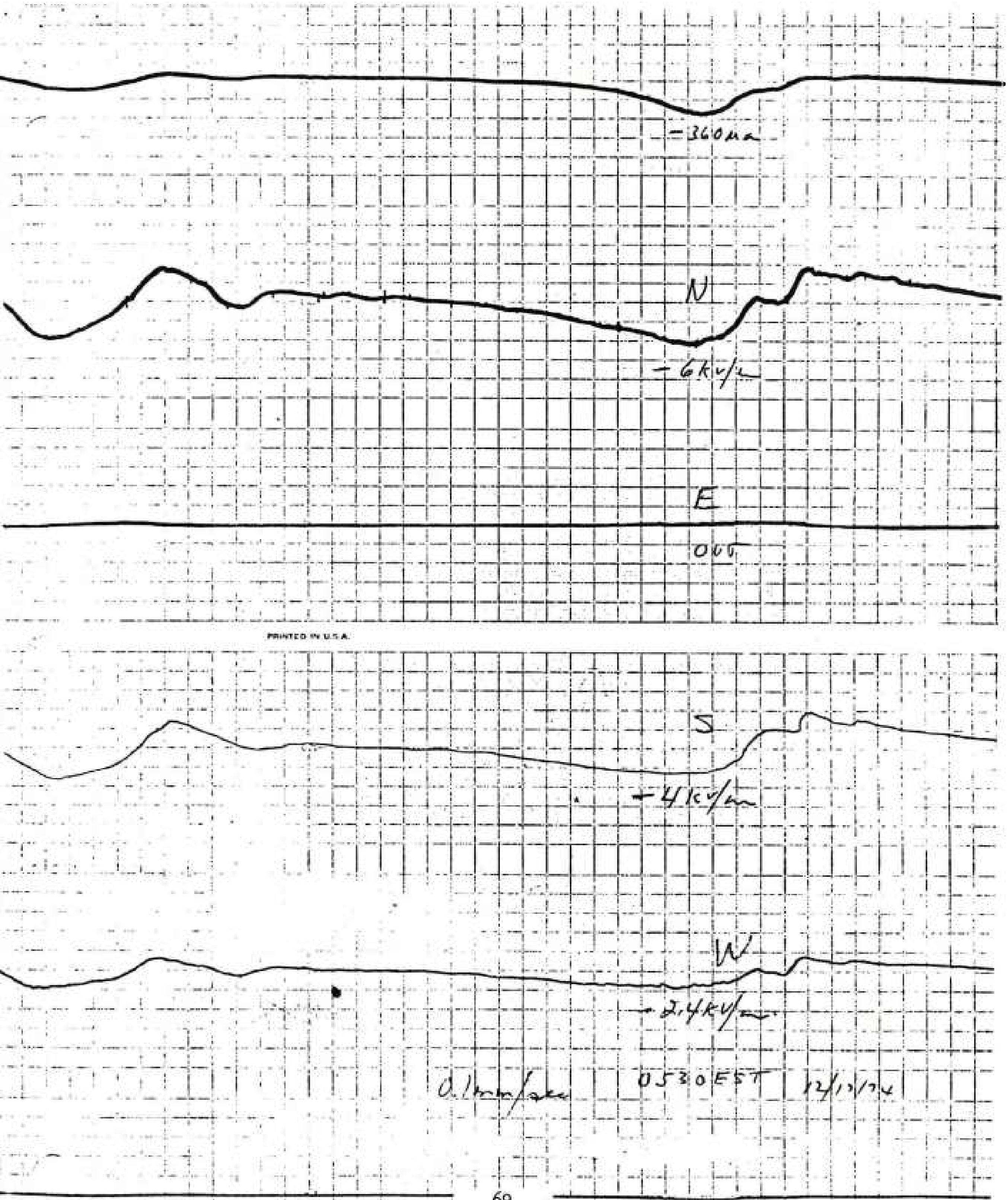
Cross sectional area of storm	2.5×10^7 m^2
Distance between upper and lower charge layer	5 km.
Upward mass flux of air	1.25×10^{11} gr/sec.
Upward flux of liquid water	2.5×10^8 gr/sec.
Rate of heat generated by condensation	6.25×10^{11} joules/sec.
Power available from heat engine	9×10^{10} joules/sec.
Rate of generating kinetic energy $\simeq$	2×10^9 joules/sec.
Total charging current	2.7 amp
Voltage between positive and negative layer	300×10^6 volts
Power dissipated as lightning	2.4×10^8 joules/sec.
Power dissipated as conduction currents	8×10^8 joules/sec.

Slide 2

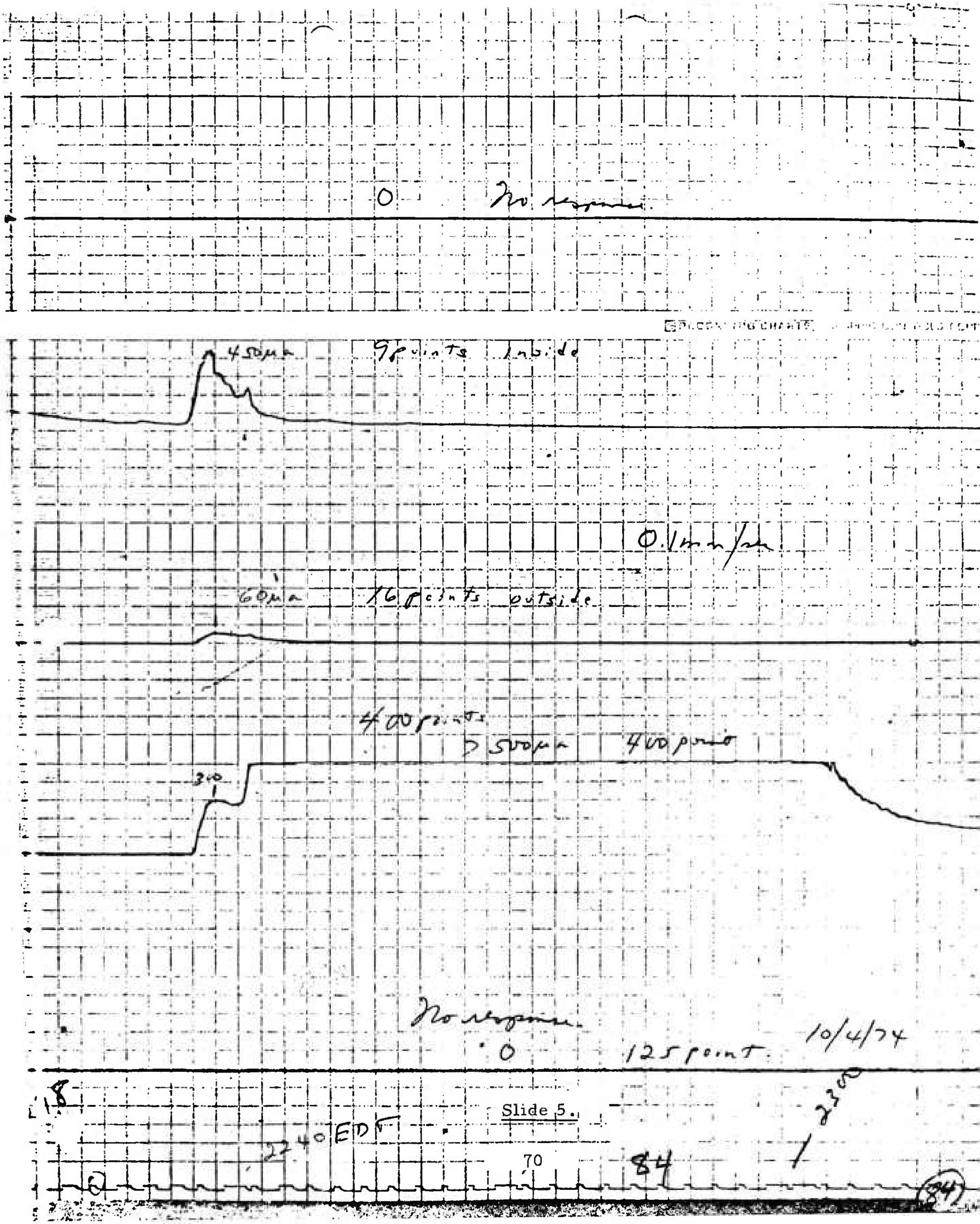

0.1mm/sec 2055 EDT 9/24/74
N
E
GRAPHIC CONTROLS CORPORATION BUFFALO, NEW YORK
S
W

Slide 3.

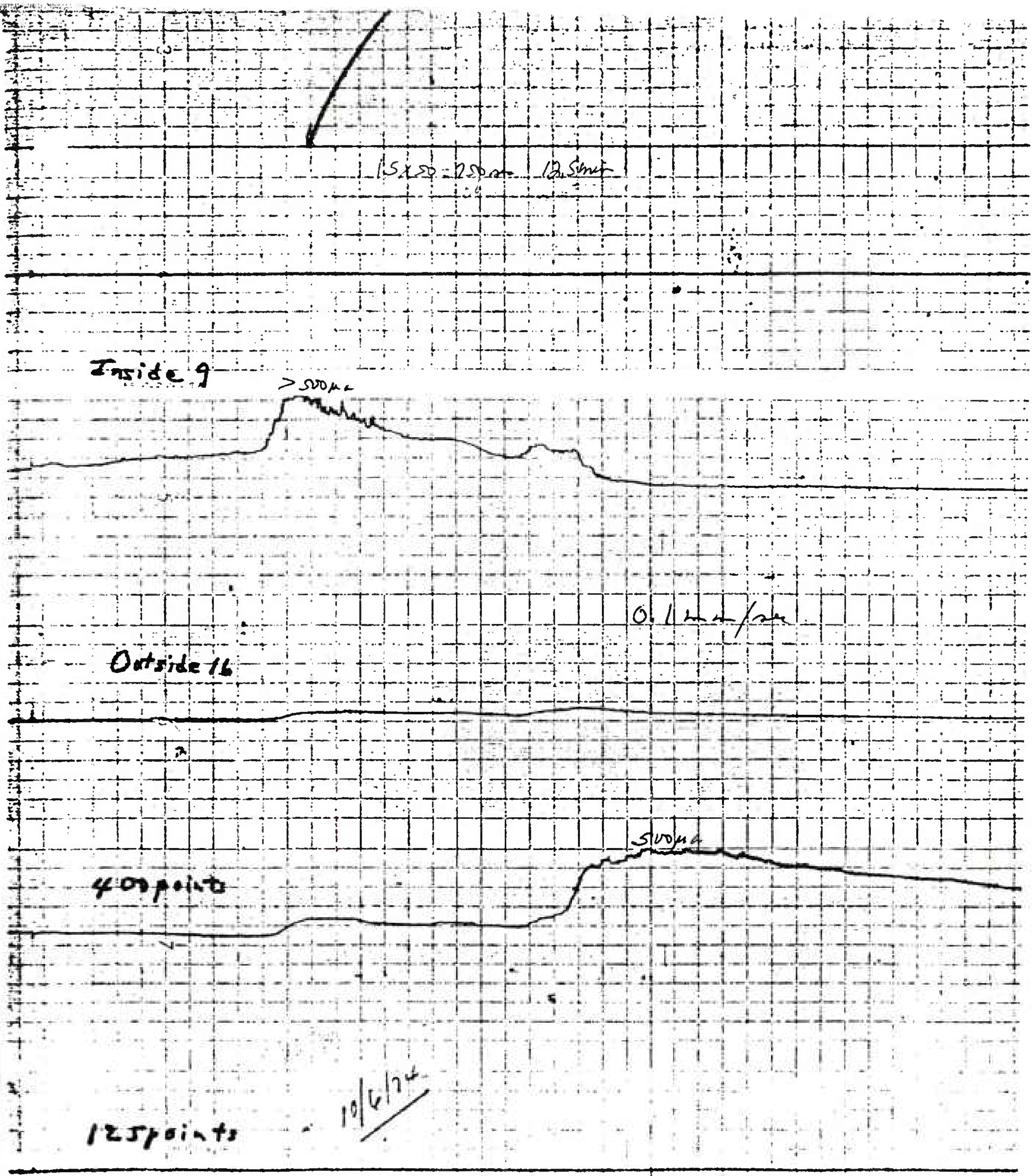
82



Slide 4.


0 No response
450μa 9 points inside
0.1mm/sec
60μa 16 points outside
400 points
> 500μa 400 points
310
No response
0 125 point
10/4/74
2300
18
2240 EDT
84

Slide 5.

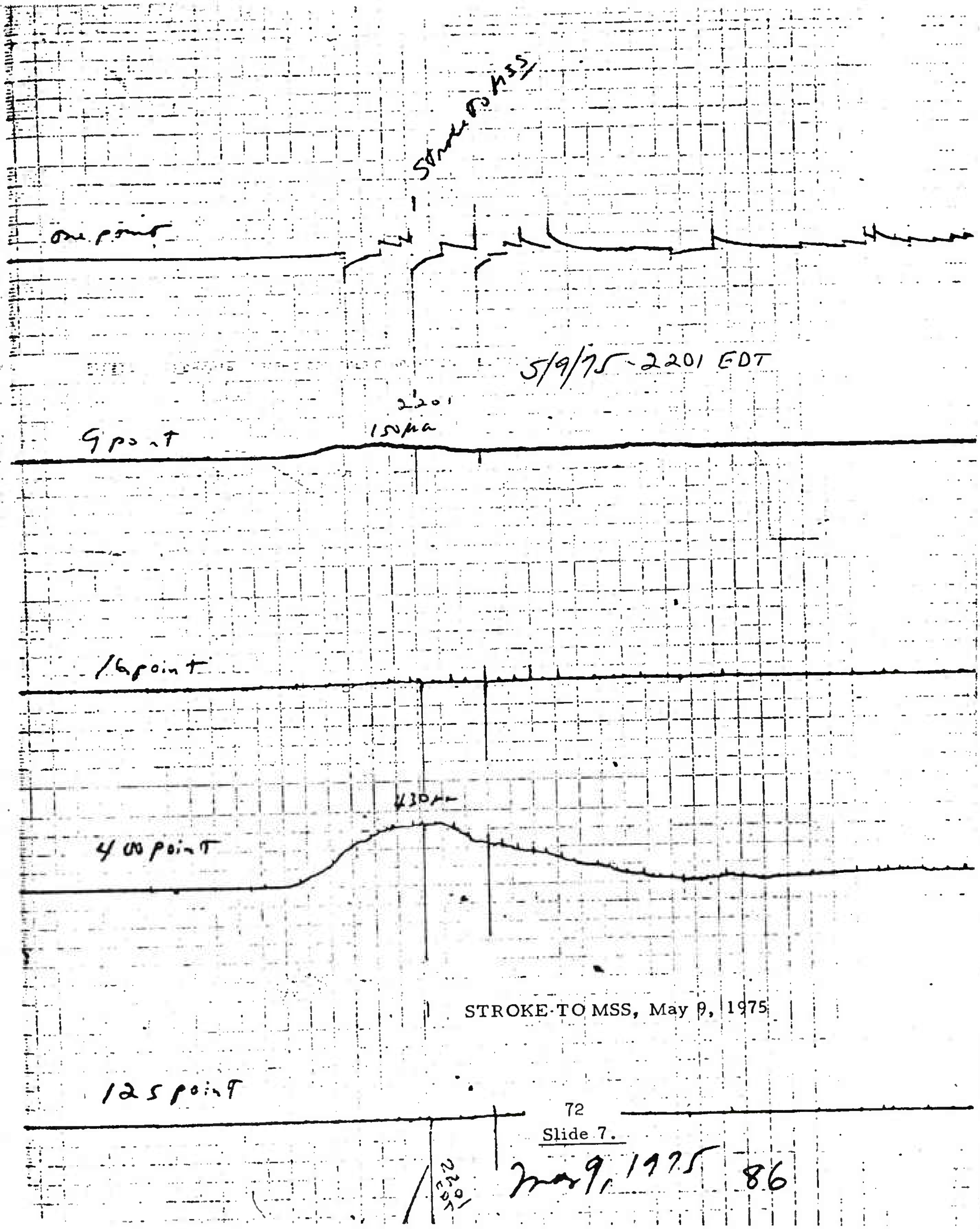


Slide 6.

3540

85

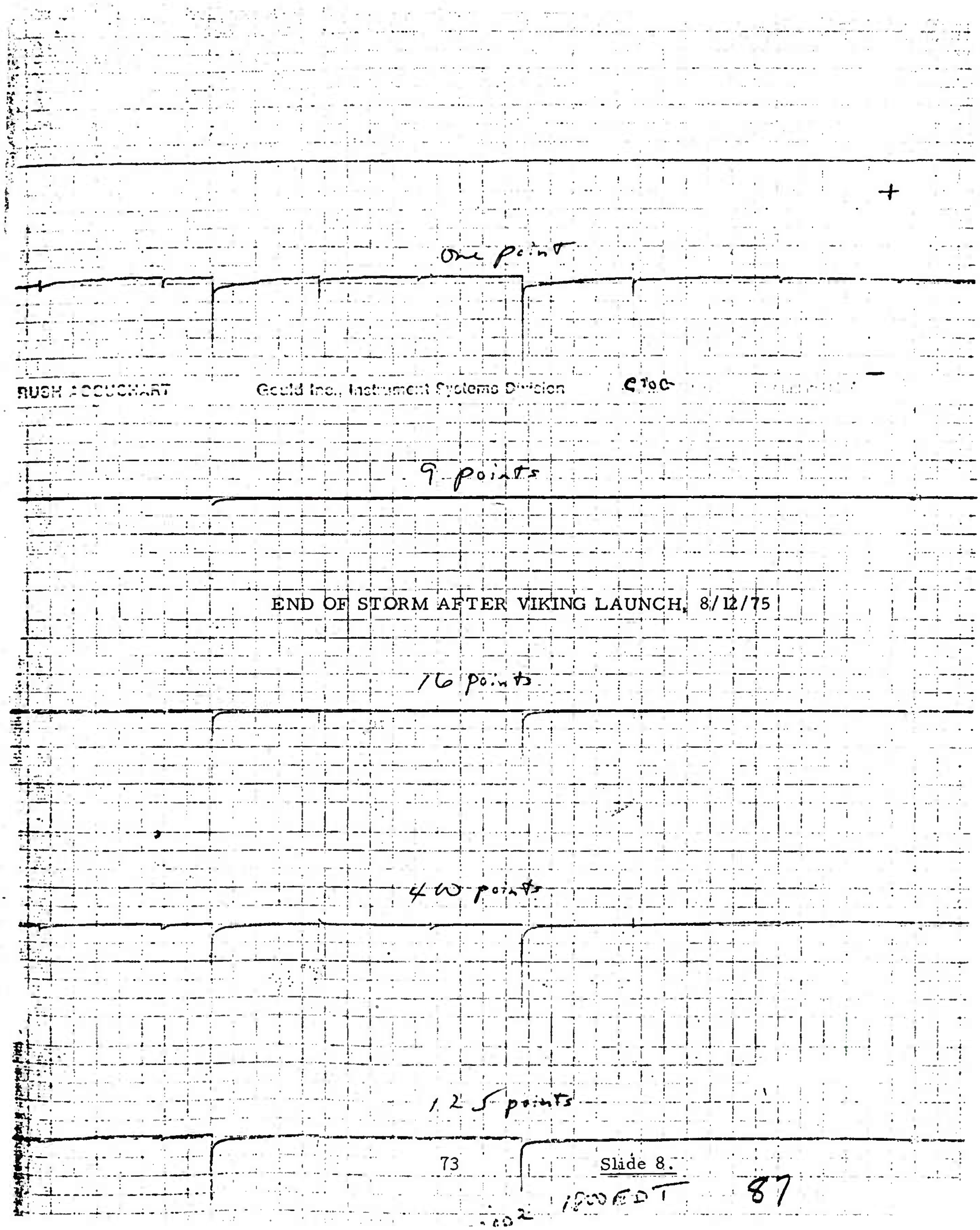
85



STROKE TO MSS, May 9, 1975

Slide 7.

May 9, 1975 86



END OF STORM AFTER VIKING LAUNCH, 8/12/75

Slide 8.

LIGHTNING INSTRUMENTATION
ON THE
500 FT WEATHER TOWER
AND
MOBILE SERVICE TOWER
KENNEDY SPACE CENTER

by

R. J. Wojtasinski

of

NASA/JFK Space Center
Kennedy Space Center, Florida 32899

November 6, 1975

LIGHTNING INSTRUMENTATION
ON THE
500 FT WEATHER TOWER
AND
MOBILE SERVICE TOWER
KENNEDY SPACE CENTER

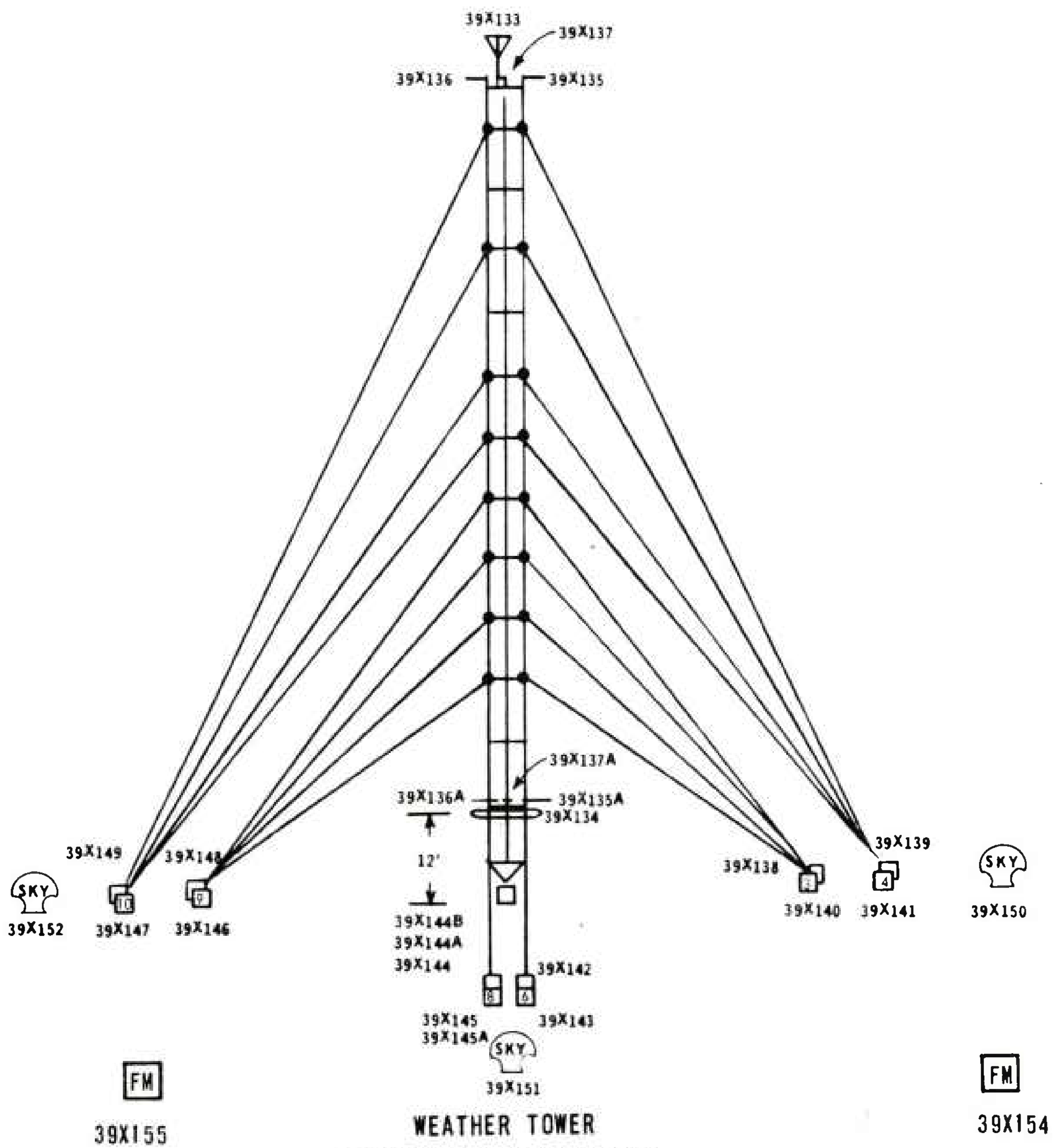
R.J. WOJTASINSKI

MEASUREMENTS LOCATION

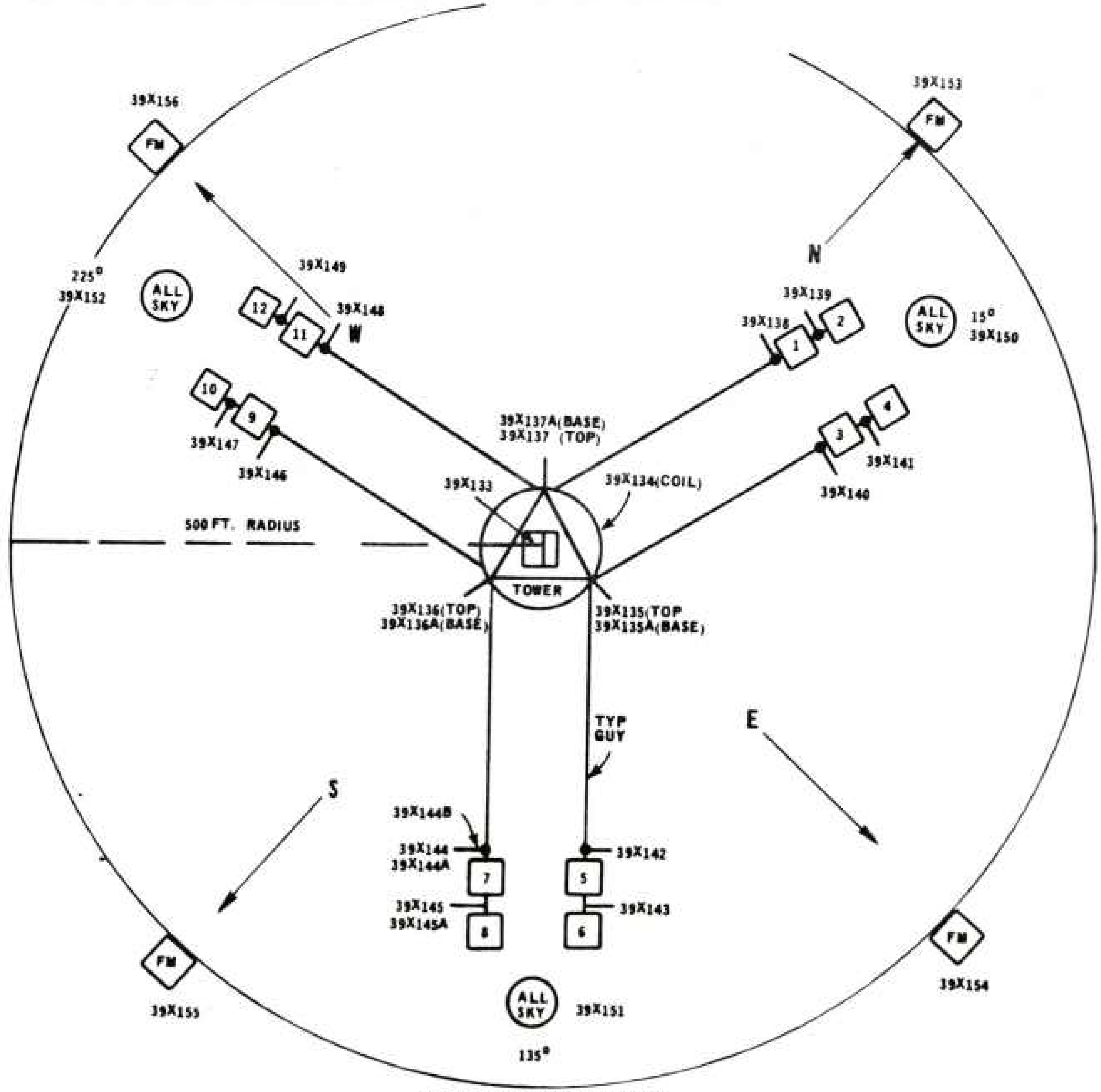
MEAS. NUMBER	TYPE	LOCATION
39X133	CURRENT ARRAY	ATOP 150 METER TOWER
39X134	LTG. WAVEFORM	BASE OF 150 METER TOWER (APPROX 12 UP)
39X135	MAG LINK	ATOP 150 METER TOWER (ESE)
39X136	MAG LINK	ATOP 150 METER TOWER (SSW)
39X137	MAG LINK	ATOP 150 METER TOWER (NW)
39X138	MAG LINK	NEAR GUY ANCHOR #1, 150 METER TOWER
39X139	MAG LINK	NEAR GUY ANCHOR #2, 150 METER TOWER
39X140	MAG LINK	NEAR GUY ANCHOR #3, 150 METER TOWER
39X141	MAG LINK	NEAR GUY ANCHOR #4, 150 METER TOWER
39X142	MAG LINK	NEAR GUY ANCHOR #5, 150 METER TOWER
39X143	MAG LINK	NEAR GUY ANCHOR #6, 150 METER TOWER
39X144	MAG LINK	NEAR GUY ANCHOR #7, 150 METER TOWER
39X145	MAG LINK	NEAR GUY ANCHOR #8, 150 METER TOWER
39X146	MAG LINK	NEAR GUY ANCHOR #9, 150 METER TOWER
39X147	MAG LINK	NEAR GUY ANCHOR #10, 150 METER TOWER
39X148	MAG LINK	NEAR GUY ANCHOR #11, 150 METER TOWER
39X149	MAG LINK	NEAR GUY ANCHOR #12, 150 METER TOWER
39X150	ALL SKY CAMERA	150 METER TOWER (NNE)
39X151	ALL SKY CAMERA	150 METER TOWER (SE)
39X152	ALL SKY CAMERA	150 METER TOWER (WSW)
39X153	FIELD MILL	150 METER TOWER (N)
39X154	FIELD MILL	150 METER TOWER (E)
39X155	FIELD MILL	150 METER TOWER (S)
39X156	FIELD MILL	150 METER TOWER (W)

EXPERIMENTAL MEASUREMENTS

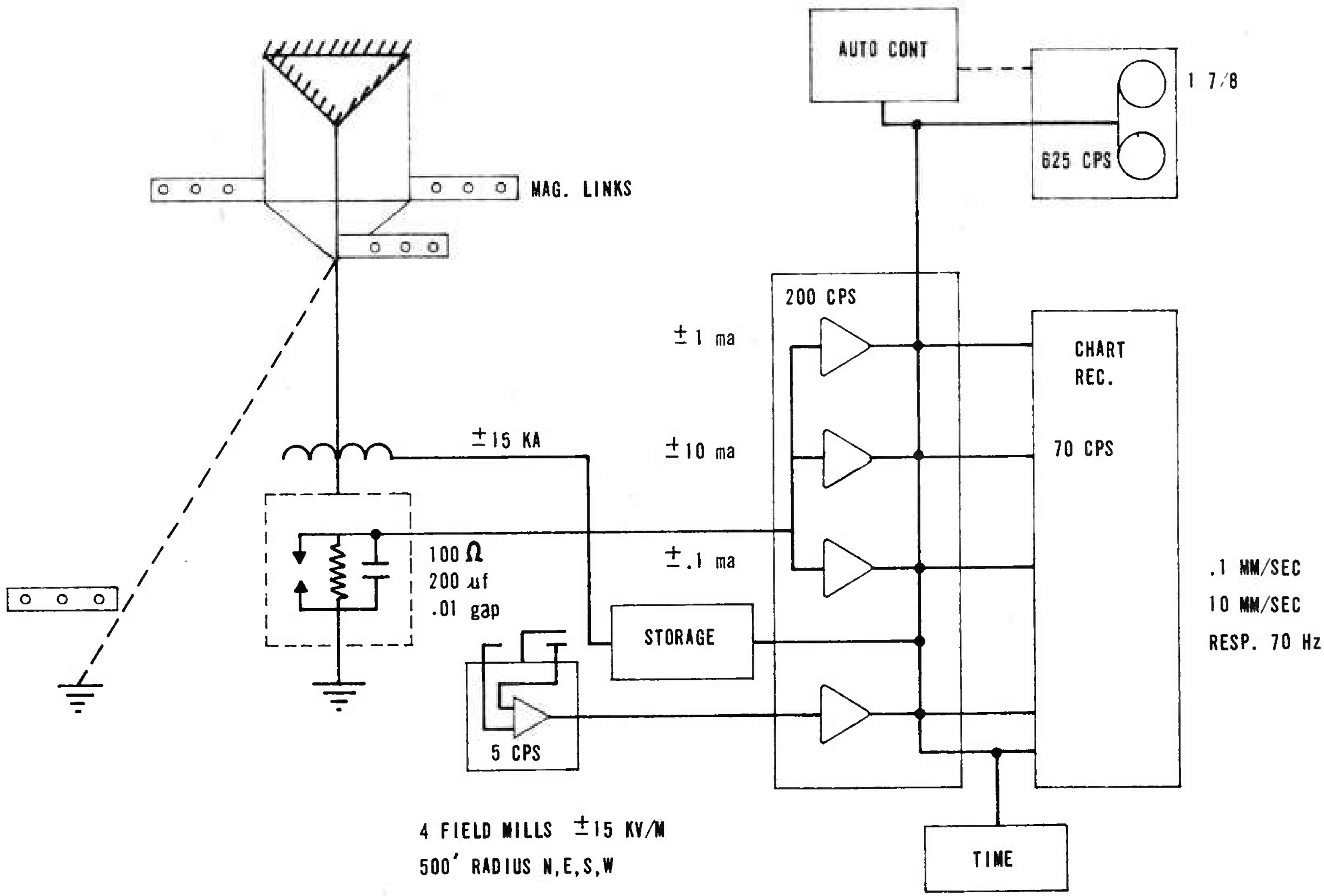
MEAS. NUMBER	TYPE	LOCATION	REMARK
39X135A	MAG. LINK	BASE OF 150 METER TOWER (ESE)	5″ ONLY
39X136A	MAG. LINK	BASE OF 150 METER TOWER (SSW)	5″ ONLY
39X137A	MAG. LINK	BASE OF 150 METER TOWER (NW)	5″ ONLY
39X144A	MAG. LINK	GUY ANCHOR #7, 150 METER TOWER	3″ ONLY
39X144B	MAG. LINK	NEAR GUY ANCHOR #7, 150 METER TOWER	3″ ON 39X144
39X145A	MAG. LINK	GUY ANCHOR #8, 150 METER TOWER	5″ ONLY



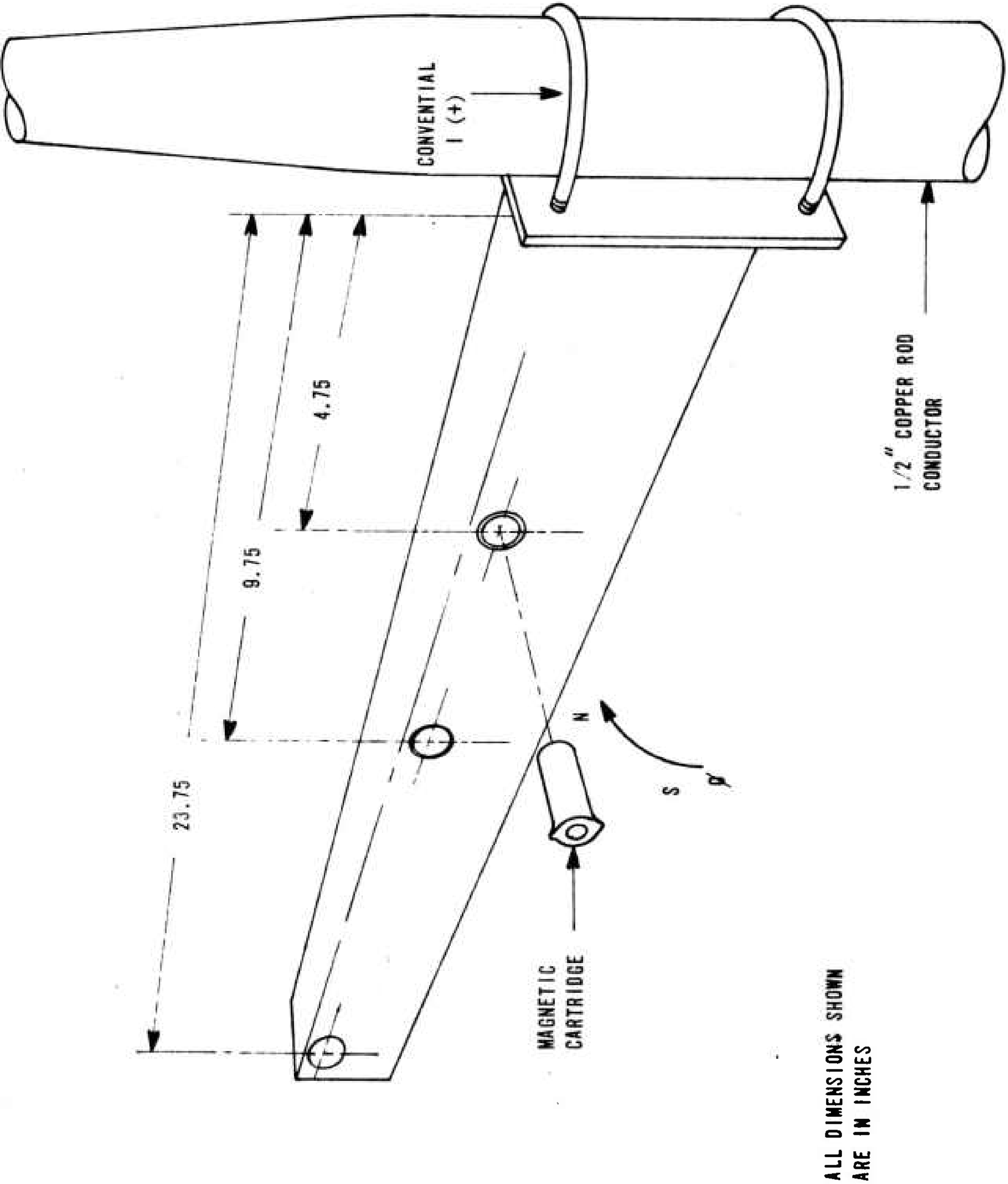
WEATHER TOWER
LIGHTNING MEASUREMENTS



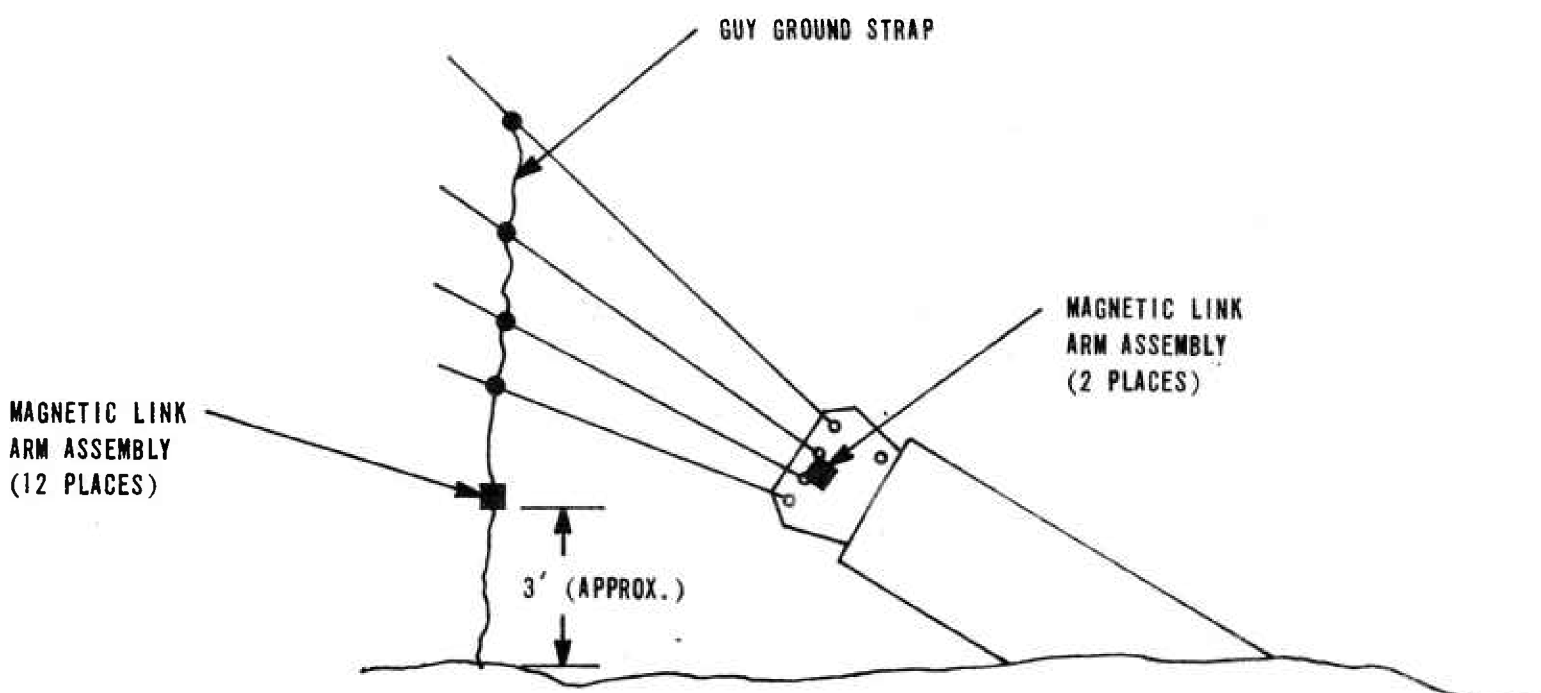
TOP VIEW LIGHTNING
WEATHER TOWER MEASUREMENTS



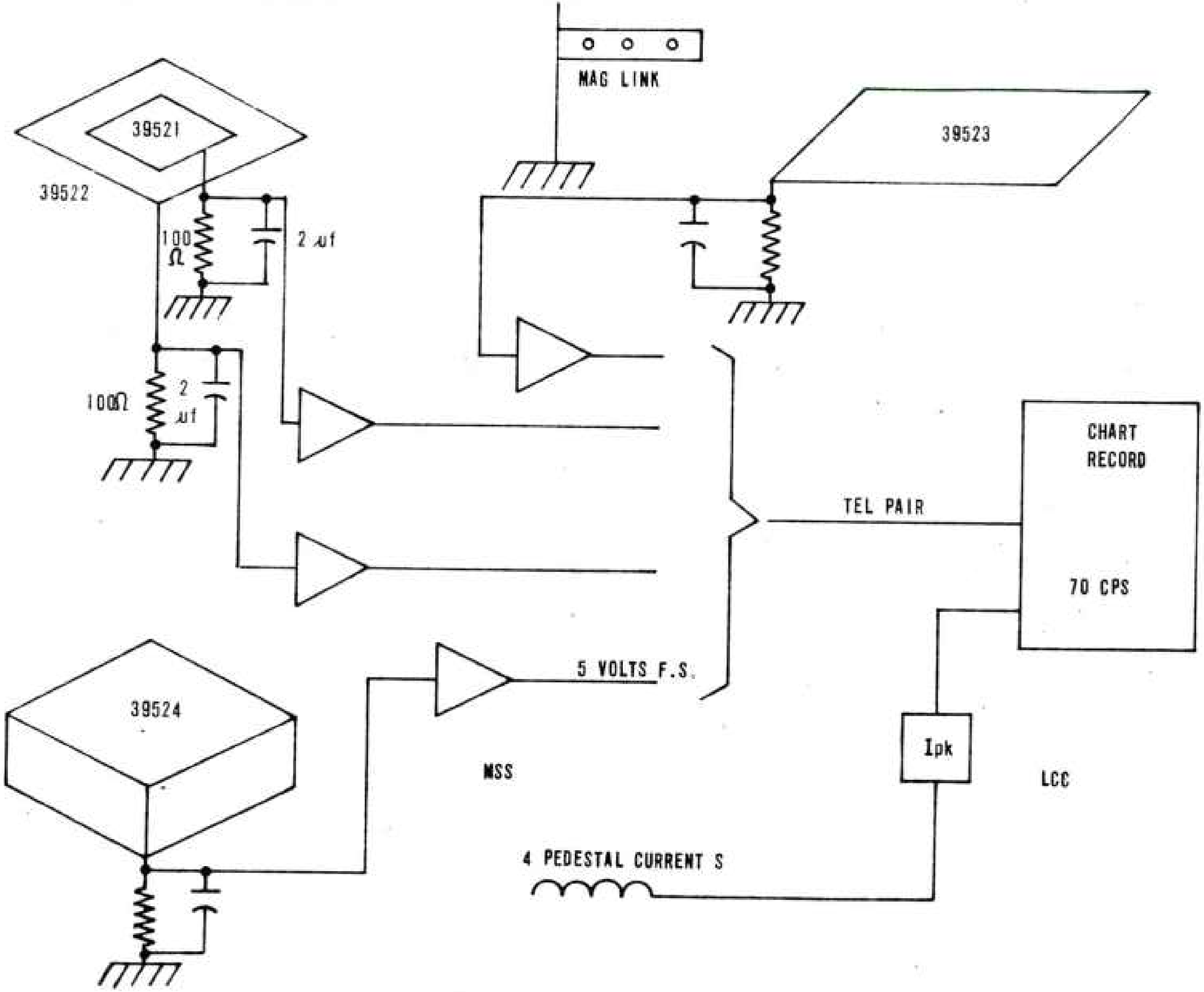
150 M. TOWER LIGHTNING INSTRUMENTATION



TYPICAL MAGNETIC LINK LIGHTNING DETECTOR



TYP. GUY ANCHOR (SIDE VIEW)



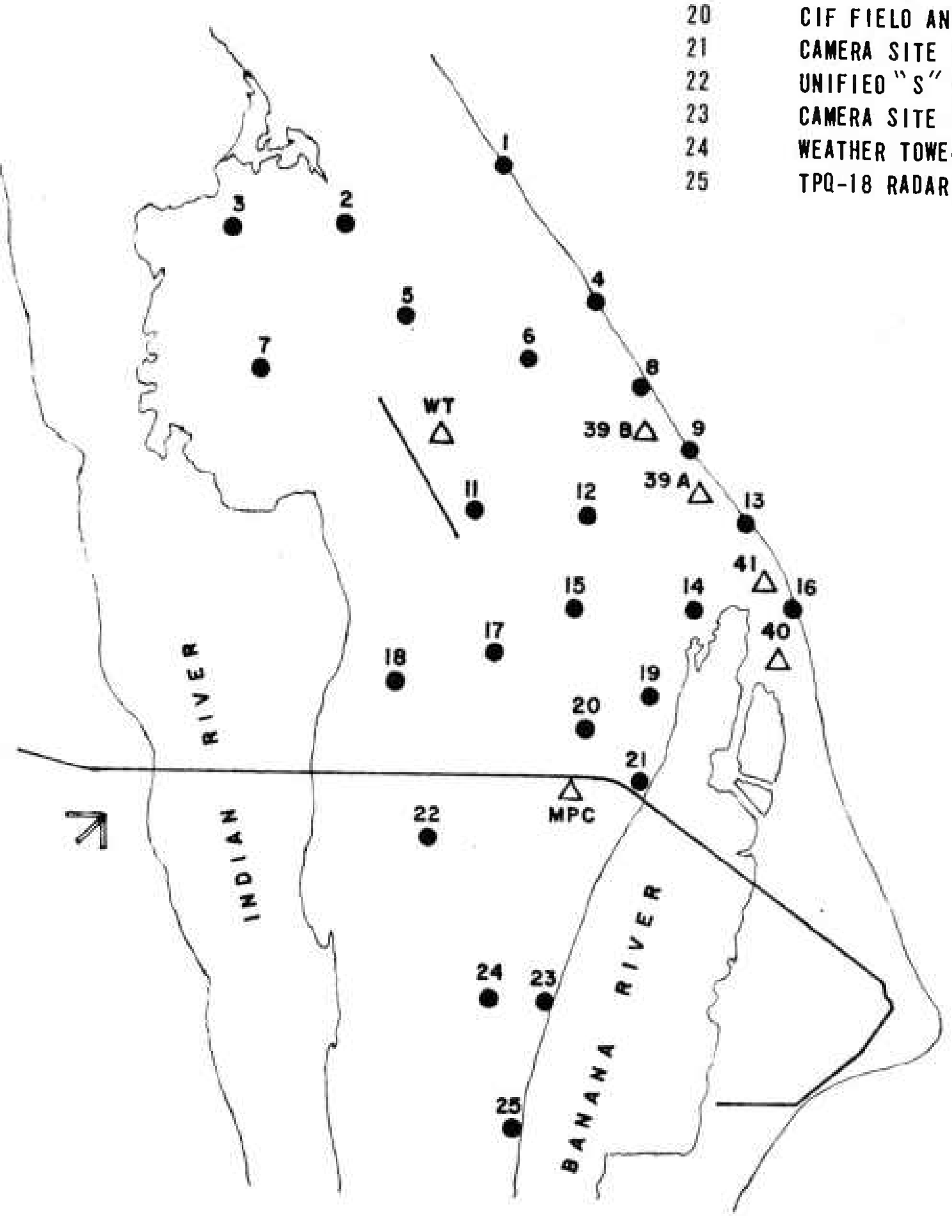
MSS ARRAY CURRENT MEASUREMENT

MSS LIGHTNING INSTRUMENTATION

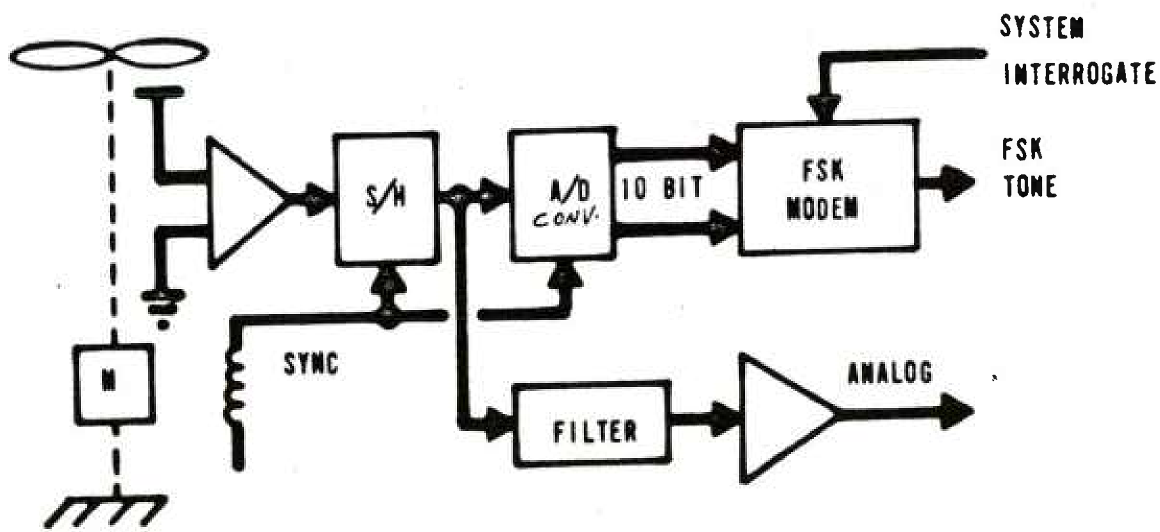
MEAS NUMBER	MEAS RANGE	MEASUREMENT DESCRIPTION
39S 21	500 UA	CORONA CURRENT, FROM ARRAY 1 MOUNTED ATOP THE MSS. INNER 9
39S 22	500 UA	CORONA CURRENT, FROM ARRAY 1 MOUNTED ATOP MSS, OUTER 16 POINTS
39S 23	500 UA	CORONA CURRENT, FROM ARRAY 2 MOUNTED ATOP MSS, 400 POINTS
39S 24	500 UA	CORONA CURRENT, FROM ARRAY 3 MOUNTED ATOP MSS 125 POINT CUBIC
39S 18	0/200 KA	PEAK STROKE CURRENT, TOP OF LIGHTNING MAST
39S 17	0/200 KA	CURRENT INDUCED CURRENT TOP OF LIGHTNING MAST
39S 18	100 KA	MAGNETIC LINK, TOP OF LIGHTNING MAST
39S 19	100 UA	CORONA CURRENT, TOP OF MSS
39S 20	200 KA	LIGHTNING CURRENT WAVEFORM TOP OF LIGHTNING MAST
42S 01	10 KA	CURRENT, MSS THRU PEDESTAL A
42S 02	10 KA	CURRENT, MSS THRU PEDESTAL B
42S 03	10 KA	CURRENT, MSS THRU PEDESTAL C
42S 04	10 KA	CURRENT, MSS THRU PEDESTAL D

SITE NO.	LOCATION
1	CAMERA SITE 10
2	WEATHER TOWER 11
3	WEATHER TOWER 12
4	CAMERA SITE 9
5	WEATHER TOWER 10
6	CAMERA SITE 5
7	CAMERA SITE 13
8	CAMERA SITE 4
9	CAMERA SITE 7

SITE NO.	LOCATION
11	WEATHER TOWER 8
12	WEATHER TOWER 7
13	CAMERA SITE 12
14	CAMERA SITE 15
15	UDOP TRANSMITTER
16	CAMERA SITE 3
17	WEATHER TOWER 6
18	FREQUENCY CONTROL SITE
19	WEATHER TOWER 1
20	CIF FIELO ANTENNA SITE
21	CAMERA SITE 2
22	UNIFIEO "S" BAND SITE
23	CAMERA SITE 1
24	WEATHER TOWER 5
25	TPQ-18 RADAR SITE



KSC ELECTRIC FIELD MILL NETWORK



KSC FIELD MILL

EGLIN REPORT

Paper given by

Marlin Forstrom, Code TSGGL

of

U.S.A.F.
ADTC
Eglin Air Force Base,
Florida 32542

November 6, 1975

<u>EGLIN REPORT</u>
November 6, 1975

Marlin Forstrom, Code TSGGL
U.S. Air Force, ADTC
Eglin Air Force Base, Florida 32542

The 1200-foot tower at Test Site C-9, Eglin AFB, was initially constructed as part of a Fixed Telemetry Station (FTS). This Fixed Telemetry Station was part of the Air Force Weapons Effectiveness Testing (AFWET) instrumentation system. Its function was to receive TM data from airborne test elements and relay these data via a microwave radio link to the Data Central Facility for insertion into the AFWET computer.

In addition to the standard tower lighting, the following equipment was installed:

1. L-band antenna (TM), RF preamplifiers, coax switches and a lightning rod at the top.

2. VHF antenna array (voice communications)installed at approximately the 800-foot level.

3. A VHF antenna array for kill/time at the 400-foot level.

4. A parabolic dish microwave antenna at the base of the tower with a passive reflector at the 366-foot level.

5. A VHF voice communication antenna array at the 250-foot level.

The only source of lightning damage history prior to the installation of the Lightning Elimination Associates (LEA) lightning dissipation array is the site log books. The data pertaining to lightning from these log books are contained in Appendix 1, History of Lightning Damage at C-9 1200-foot Tower, of the Interim Report on Lightning Dissipation Arrays by Atlantic Science Corporation dated September 1975. (This paper is presented in this publication).

At this time, I would like to present a film titled "A Novel Approach for Elimination of Lightning" which covers the installation of the original array at the 1200-foot tower at Eglin AFB.

Starting from 30 September 1972, the history of lightning effects to the 1200-foot tower and/or associated equipment is extracted from various reports and letters, in addition to the site log books. The following is the 30 September 1972 (Saturday) data from an LEA Interim Report on Dissipation Array Performance dated 31 October 1972:

"A more significant phenomena is that indicated by the sharp peaks displaying no subsequent exponential decay. These are usually cloud to ground strokes where they merely introduce an electrostatic transient into the system. However, in this case an unusual

phenomena was evident, a wire connecting the grounded end of the array with the ground of the recorder was instantly vaporized; indicating a very high flow of current within the system. See Figure 10 for the test setup diagram.

"Inspection of the instrumentation revealed the obvious results of a large flow of energy somewhere within the system. None of the load resistors were harmed. Only the one-inch piece of number 16 solid copper wire, used to provide a grounding point for the Brush recorder, has been influenced. It completely disappeared. There are two protective spark gaps across the recorder input terminals, subsequent measurements indicated both displayed above five megohms resistance in both directions, no damage. No other manifestations were found. A subsequent check of the array also indicated no signs of damage."

The conclusion section of this same report states that:

"The transient surge of the 30 September run must be attributed to one or a combination of two factors, either one of which would have permitted the surge. The ground connection for the array had to be poor at best, otherwise the current would have followed that path, the most logical (lower resistance) path. The existence of the surge can only be explained as a direct contact between the array and a charged cloud, one that had seen very little dissipation. The poor grounding and/or the low aspect angle between the array face and the cloud base would have accounted for this phenomena."

The site log book for this date contained the following entries:

30 Sep 72 - M/W on the phone. Use inner probe setup. Storm over top, so started recording.

0822 - Apparent direct hit on tower.

0823 or 24 - Second apparent hit on array. Turned tower lights off for test. Stop chart recorder. Mr. Meyers on site to set up outer probe.

1040 - Base weather says front here. Virtually no dissipation from array.

The following entries are extracted from the site log book for the period 2 October 1972 to 13 November 1972:

2 Oct 72 - Outside shack light and one obstruction light out. Mr. Huntley on site - took photographs of lightning damage to recorder, etc., during Saturday's storm. Elevator would not work. Ground return to main power pole rewired.

5 Oct 72 - Mr. Evans and Mr. Beaman inspect array. No physical signs of damage. Resistance from array to tower (ground line removed) = 350 ohms. Resistance from array test wire to tower = 2.5 megohms.

10 Oct 72 - Resistance check .3 ohm.

13 Oct 72 - Meyers up tower to try and improve insulation of the array from tower. Completed refastening outer probe ground (LEA) back to wire that runs back to balloon site for its ground. Mr. Meyers on way down tower - had difficulty locating a short from array to ground.

16 Oct 72 - Resistance .3 ohm.

17 Oct 72 - 1145 - Mr. Hoffman says the last storm damaged cards in the boxes (amplifier boxes up tower).

24 Oct 72 - Resistance .3 ohm. LEA array 500 kilohms.

6 Nov 72 - Resistance .3 ohm.

7 Nov 72 - Storm to North. Not much dissipation.

10 Nov 72 - Recorders on most sensitive scale. No signs of much dissipation.

13 Nov 72 - LEA resistance 100 kilohms.

The following data summary from 13 November 1972 is taken from an attachment to an LEA letter, subject: "C-9 Data Analysis, 7 and 13 Nov Runs", dated November 24, 1972:

"(2) 13 November Run: An extended storm front moved through the C-9 area on 13 November 1972. It started at about 1245 and extended through 1830, lasting over 6 1/2 hours in duration. Several cell complexes moved over C-9, some of which actually engulfed the top third of the tower. Dissipation currents rose and fell with the cell movement and its proximity with respect to the tower. The current peaks reached over 2400 microamperes and remained there, often for extended periods of time, with and without the usual cloud-to-cloud discharges. Table 2 presents a chronological summary of these data, time synchronized with scattered inner and outer probe data. Figure 1 presents two significant segments of array data; while Figure 2 presents two significant segments of probe data. 100 to 1 differences are noted between peaks; however, there is over 1000 to 1 differences in the energy level. Thunder was sounded as close as one mile. The cloud-to-cloud flashes were noted during some periods and not during others. Segment B of Figure 1 reveals close cloud-to-cloud flashes and lower dissipation current than Segment A which presents a compound situation with both close and distant cloud-to-cloud flashes and some ground strokes."

The significance of these data lies in the following conclusions drawn from these data in the same report:

> "The fact that the tower was engulfed by clouds indicates that there was a path for large current flow such as that found during the 30 September run. However, since no such phenomena was noted, it is safe to assume that whatever caused that situation may have been corrected."

The following entries from the site log book cover the period 30 November 1972 to 2 January 1973:

20 Nov 72 - Resistance .3 ohm. LEA 200 kilohms.

29 Nov 72 - LEA 140 kilohms. Resistance .3 ohm.

30 Nov 72 - LEA 21 kilohms.

4 Dec 72 - .3 ohm and 3 kilohms. Very low dissipation.

6 Dec 72 - Low dissipation.

11 Dec 72 - 25 kilohms. .3 ohm.

19 Dec 72 - .3 ohm. 280 kilohms.

20 Dec 72 - Reverse meter leads to array, different values, 200 kilohms average. This goes higher if antenna leads are disconnected from antenna, so part of leakage is through antenna leads.

26 Dec 72 - .3 ohm, 70 kilohms.

2 Jan 73 - All NE obstruction lamps, one south and one beacon lamp out. Several lamps out - antenna switch at top damaged. F6 10 amp fuse blown in tower lighting box (NE lamps).

The following is quoted from a letter from ADTC/TSGGL, Eglin AFB, to LEA dated 15 March 1973:

> "1. During a heavy overcast and thunderstorm on 7 March the dissipation array was hit by lightning. The lightning hit the top of the TLM (CHU Associates) antenna mounted on top of the array and followed the antenna cable to an antenna relay where it got on the 110 volt power line seeking a good ground.
>
> "2. The strike burned out the antenna relay and put a surge on the power line which blew several light bulbs in the data van and shack and opened the pumb motor circuit breaker in the restroom. A 48 volt

power supply (H-P 6206B) for the microwave system was disabled. Two temperature and dewpoint amplifiers at the top of the tower had blown fuses and one was disabled. The two amplifiers at the bottom of the tower were still OK.

"3. Inspection of the instrumentation and data taken indicated that a poor connection to the array and the high series resistor reduced the efficiency of the array to the point where it did not dissipate enough of the cloud energy to make it effective, i.e., for a 20-minute period the array only dissipated .086 coulombs of energy which is low by a factor of at least several hundred.

"4. The following corrective action is being taken to insure that the dissipation array is operating at optimum efficiency.

a. Site personnel will perform periodic inspection of the array and down lead to see that all connections are clean and secure.

b. The dissipation array series resistor will be reduced to 1000 ohms when buildup is occurring and 10 ohms when charged clouds approach the tower.

c. The TLM (CHU Associates) antenna will be mounted directly on the array with both ground and hot side of antenna connected to the TLM box through isolating capacitors. Until this change is made the antenna coax lead will be disconnected at the antenna during a storm."

The following entry from the site log book agrees with this letter:

8 Mar 73 - CHU Associates antenna shorted to array. Fixed it. Also, the Curnie nut that holds the array ground wire to array was loose and corroded. Fixed.

The following entries from the site log book cover the period 4 June 1973 to 15 August 1973:

4 Jun 73 - Power supply to bay P6 switches on and arced - smoking - switch shorted and power indicator lamp had blown hole in side of lamp holder. Men arrived to put water faucet on outside of building. No water pressure. Return ground from the pump was burned, so repaired it. No pump power. Points badly burned. Power supply to chart recorder damaged.

18 Jun 73 - Pump meter burned out - repaired 19th. Array wire burned out - discovered by William and Peacock, where it comes down.

2 Jul 73 - Pump motor burned up.

15 Aug 73 - Meyers up the tower to check out all of the switching preamps

and antennas at the top of the tower. Meyers down from tower, had to replace both switches and the CHU Associates antenna. Repaired one of the switches but did not have enough parts to repair the other. Took the Chu antenna apart to look at the damage, "was a mess."

On 17 August 1973, the array was grounded to the top of the tower as well as being grounded to the base of the tower. There are no site log book entries that indicate any lightning damage until 21 February 1974 when the array took a direct hit. The following is a memo for the record that I wrote on 26 March 1974 describing lightning damage at C-9 and C-74:

"1. On 21 February 1974 lightning damage occurred on the 1,200 foot tower at C-9. The lightning struck an antenna that extended about four feet above the Lightning Dissipation Array and an outer strand of the array. Damage consisted of a small burn on the antenna tip, burned an outer wire of the array to the extent that the wire severed, and burned a coax cable. In addition, a radio receiver and transmitter received damage from lightning. This damage did not appear to occur as a result of a direct hit on the equipment but rather an induced voltage in the remote speaker and mike lines running from the van to a building about 25 feet away.

"2. On 18 March 1974 Mr. Roy Carpenter, LEA, was contacted and informed of the lightning damage we have experienced. On 20 March 1974 Mr. Carpenter arrived at Eglin to evaluate the lightning damage at C-9. Mr. Carpenter made the following determination as to possible reasons for the strike:

a. The wire with the points had become loose allowing many of the points to be lower than other points thereby decreasing the efficiency of the array. Maximum efficiency occurs when all points are in the same plane.

b. The antenna located in the center of and extending about four feet above the array reduces the effectiveness of that part of the array nearby. This reduces the effective size of the array and thereby reduces its efficiency.

c. A check with the base weather station indicated cloud heights on that day of from 300 feet to 2,500 feet. The design of the present array has maximum efficiency when the clouds are almost directly overhead. Clouds moving into the area at a height close to the height of the array are exposed to a minimum number of points and are not discharged as effectively.

"3. Mr. Carpenter brought a 2 x 4 foot panel array of the type used for the warning system at C-74, requesting we install it on top of the 1,200-foot tower and instrument it to get comparison data with the old array. He then proposes to remove the present array and replace it with a new array at no cost to the Government. The new array will attempt to eliminate the deficiencies listed in paragraph 2 above.

"4. On 21 March 1974 Mr. Carpenter and myself departed for C-74 at 0600 hours to try and observe the lightning warning system during thunderstorm activity. However, the thunderstorm activity was just clearing the area when we arrived. In looking over the lightning warning system, we discovered that the south warning system had been struck by lightning. This caused a burned out amplifier and burned wires. The obvious conclusion reached is that the design of a warning system must be sufficient to prevent lightning as well. Again, a complete redesign of the lightning warning system will be performed by LEA at no cost to the Government and installed at C-74."

I will discuss the Test Area C-74 lightning warning system upon completion of the 1200-foot tower discussion.

During the week of 21 April 1974 the 2 x 4 foot panel array was installed on the tower with the existing array to obtain comparison data for LEA to use in the design of a new array. Also, during this week, the weather equipment was removed from the tower.

A radar beacon, TPX-42, was installed on the tower on 23 May 1974 and made operational on 5 June 1974. The log books indicate that this beacon required maintenance eight times from 5 June 1974 to 23 May 1975. A check with the maintenance personnel on Eglin Main Base indicated equipment damage (blown diodes) which could have been caused by induced voltage in the 28 VDC cable supplying power to the beacon.

The new array was installed on 28 July 1974. During the period 22 July 1974 to 28 July 1974, there was no lightning protection on the tower. On 26 July 1974 the tower was struck by lightning. The following entries from the site log book describe this event and also lightning damage that occurred on 8 January 1975:

29 Jul 74 - Lightning hit on Friday 26 Jul 74 while there was no array on top of tower. Damaged tower lights, 3 fuses, 1 photocell, telephone, VHF #1 radio (transmitter and receiver) and the well pump motor.

6 Aug 74 - We discovered that some of the wires from the keying circuit to the power supply had been burned in two by lightning. NOTE: This is part of the VHF #1 transmitter and the problem is the result of the lightning on 26 Jul 74.

7 Aug 74 - We discovered that the pump was not working, discovered the main circuit breaker was tripped in power box. We also discovered the tower to pump ground was open. We trouble shot and found return ground to be open. The lightning had blown wire in two. We have return ground replaced but haven't finished burying it yet.

9 Aug 74 - Herring and Meyers up tower to finish securing array data line.

23 Sep 74 - Discovered the data line from the array was showing open. Meyers down from tower. He said the lightning had burned or cut the data line in two where it touched the tower leg.

24 Sep 74 - Meyers up the tower to repair array data line.

8 Jan 75 - We discovered that the lightning had run in on telephone and had burned up the M/W CH unit. Discovered that we had a blown fuse in tower lighting circuit. Discovered that the lightning had burned wires in two bringing array data into personnel shed.

13 Jan 75 - Telephone maintenance AF on site to fix phone in personnel shed. They departed site. They found four fuses blown in carbon block boxes in telephone line.
NOTE: This telephone problem a result of lightning damage on 8 Jan 75.

Test Area C-74, sled track, at Eglin AFB also has a lightning protection/warning system. The protection system consists of a 5-stranded barbed wire array 1800 feet long offset from the track 100 feet and parallel to the track. This array is approximately 40 feet high. The south end of the sled track has an 85-foot tower which has an umbrella array on it. A 4 x 4 foot panel array is located adjacent to each of two CZR bunkers. These arrays are on utility poles approximately 50 feet above ground and were installed as part of a lightning warning system.

The only available data on the performance of the lightning protection system at C-74 will be in the ONR Contract Report on Field Observations and Measurements at Eglin AFB by the University of Minnesota, Duluth. There is no history of damage since all instrumentation used in this area is temporarily set up for each test and removed immediately following the test.

No attempt has been made to use the warning system as such. Up until a few weeks ago, no correlation could be made between the field strength and the corona current. These arrays have a path to ground through the utility poles displaying a resistance of less than 10 kilohms. This allows the generation of ground currents which can be an order of magnitude greater than corona current. This inserts a bias in the corona current measurements which is variable. Further tests will be conducted by Eglin AFB after the arrays are completely insulated.

In addition to the ONR Report by the University of Minnesota, which covers the events of summer and fall of 1974, an ONR Report by Atlantic Science Corporation will cover the events of the summer of 1975.

One final point, Hurricane Eloise destroyed the 1200-foot tower thereby terminating testing on this tall structure. I have several slides showing the results of Eloise.

STUDY OF BEHAVIOR OF SHARP AND BLUNT LIGHTNING RODS IN STRONG ELECTRIC FIELDS

by

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of

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November 6, 1975

Extract of Talk Given

at

Johnson Space Center, November 6, 1975

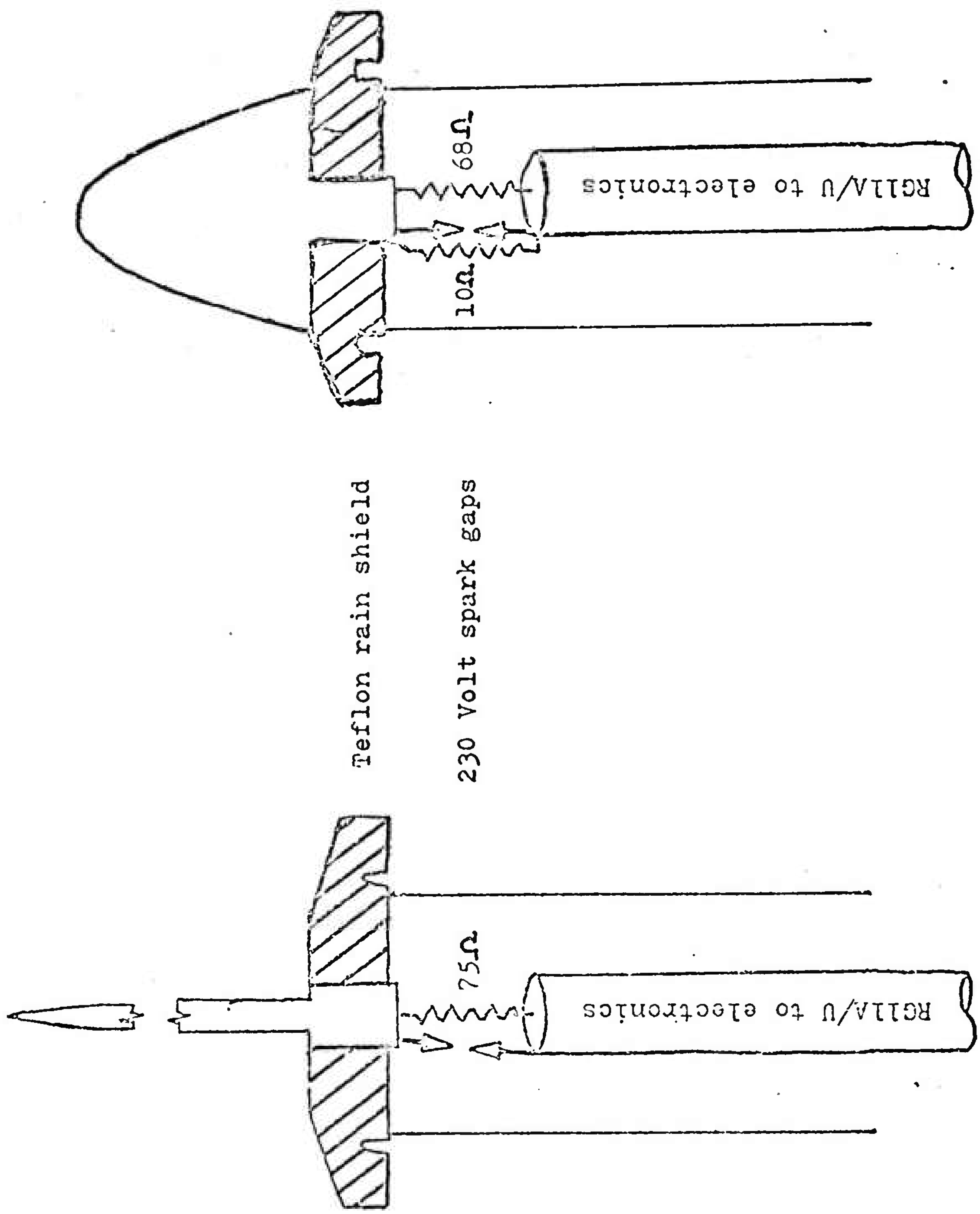
STUDY OF BEHAVIOR OF SHARP AND BLUNT LIGHTNING RODS IN STRONG ELECTRIC FIELDS

INTRODUCTION

Some years ago Bernard Vonnegut and I attempted to obtain information on the density of point discharge currents given up by the earth beneath thunderstorms in an effort to assess their role in cloud electrification. In the course of this study we erected a number of different arrays of wires, sharpened rods and tree branches, then measured the currents that would flow from them when thunderstorms developed overhead. Lightning strikes in the vicinity of our observatory were common but the failure of lightning to strike the well-exposed, sharpened rods caught our attention and subsequently led me to pursue this further. During the past few years at Langmuir Laboratory several students and I have been attempting to determine the reasons for this apparently anomalous behavior. In the most recent work, one of our students, Ronald Standler, erected two masts each 9 meters high and separated perpendicular to the normal wind by about 20 meters so that they did not interfere with each other. On the top of one mast he placed a very sharp stainless steel point with a tip radius curvature of about .1 of a millimeter; on the other mast he placed a blunt rod with a radius of curvature of 5 millimeters. Each of the tips were connected to ground through an integrating ammeter circuit and recorded on a strip chart oscillograph. The frequency response of the integrator and recorder system was of the order of 100 Hz. Figure 1 shows the tip arrangement.

Some of the results of these measurements are shown in Figures 2 through 5. Under strong electric fields, the sharp rod emitted point discharge with flows of a few microamperes. When no transients occurred in the normally strong electric fields beneath thunderstorms, on the other hand, the blunt rod was passive and emitted no currents.

When lightning occurred at a distance, the impulsive changes in the electric field caused displacement currents to flow in both exposed rods and point discharge currents were emitted from both. With lightning at great distances only the sharpened rod emitted point discharge currents but for the larger field changes associated with nearer lightning strokes the blunt rod emitted transient bursts of ions also. The behavior of the two rods shows a significant difference as the field changes became larger yet. The sharp rod at all times emitted readily the charges required by the electric field whereas the blunt rod usually emitted little charge until the field became very intense. With the approach of a negative



Teflon rain shield
230 Volt spark gaps
68Ω
10Ω
75Ω
RG11A/U to electronics
RG11A/U to electronics

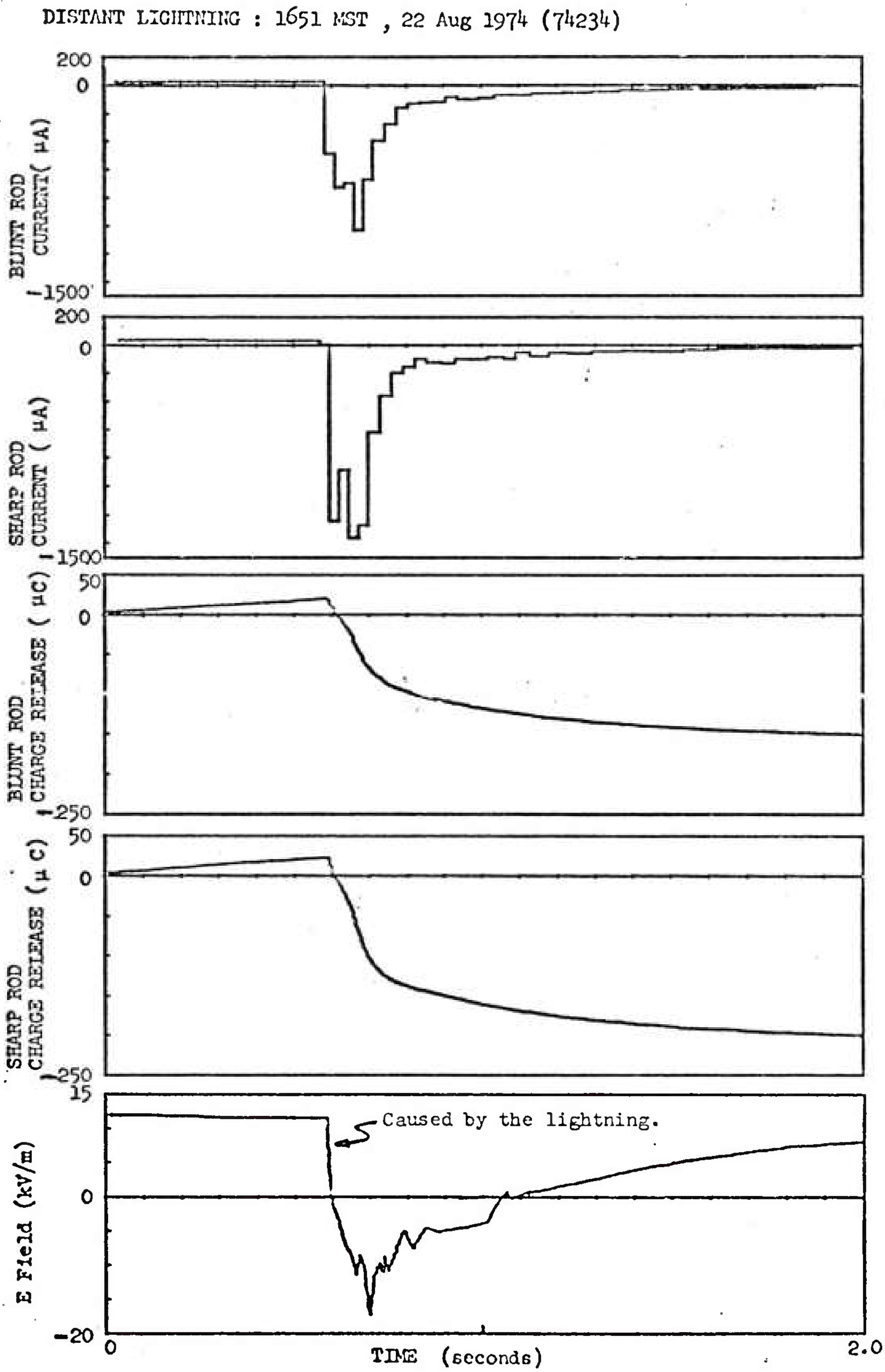

DISTANT LIGHTNING : 1651 MST , 22 Aug 1974 (74234)
200
0
-1500
BLUNT ROD CURRENT(μA)
200
0
-1500
SHARP ROD CURRENT (μA)
50
0
-250
BLUNT ROD CHARGE RELEASE (μC)
50
0
-250
SHARP ROD CHARGE RELEASE (μ C)
15
0
-20
E Field (kV/m)
Caused by the lightning.
0
2.0
TIME (seconds)

Figure 2

LIGHTNING 3.3 km from observatory at 1152MST ,18 Aug 1974 (74230)

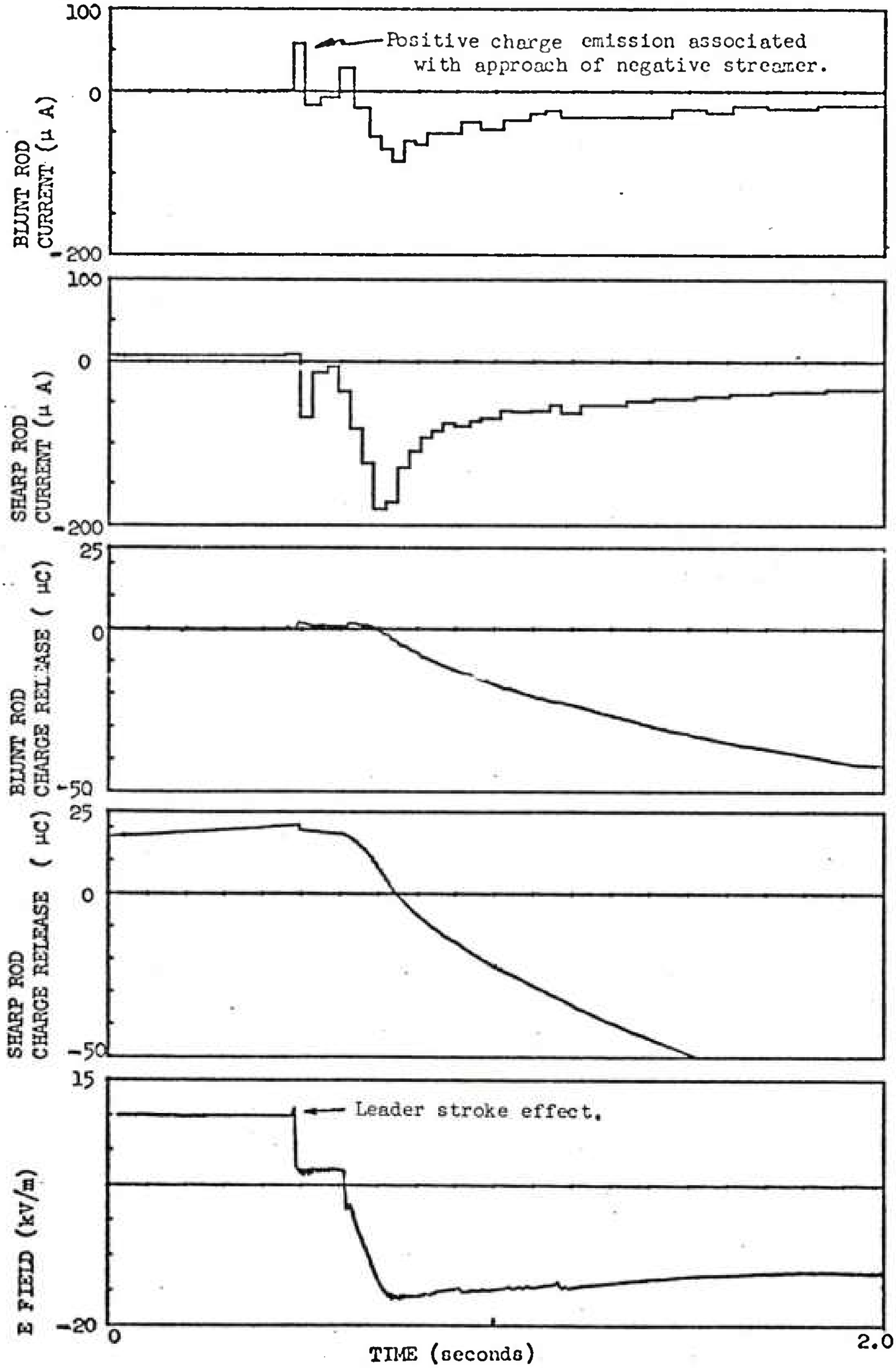


Figure 3

LIGHTNING 1.2 km from observatory at 1138 MST , 18 Aug 1974 (74230)

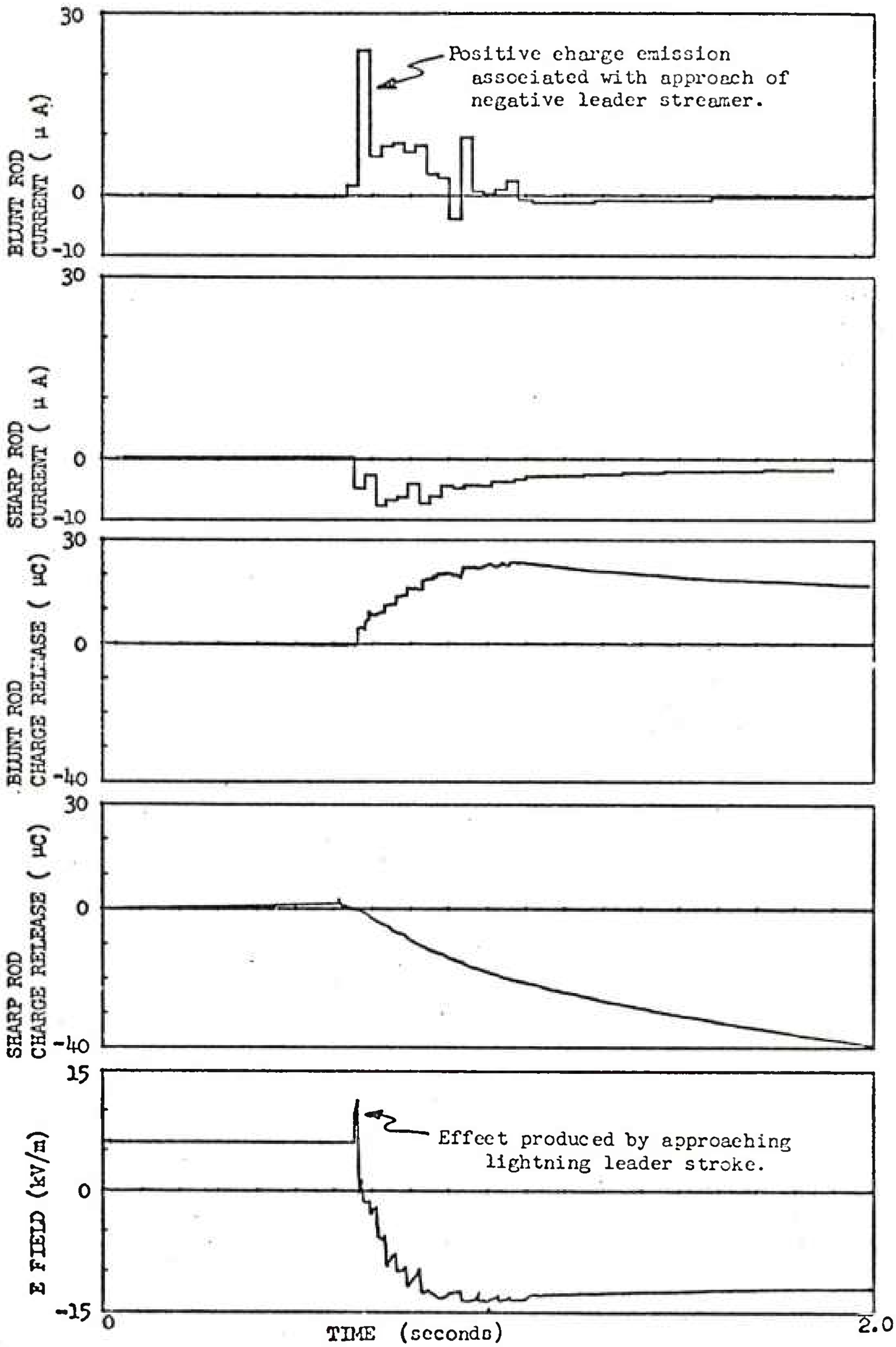
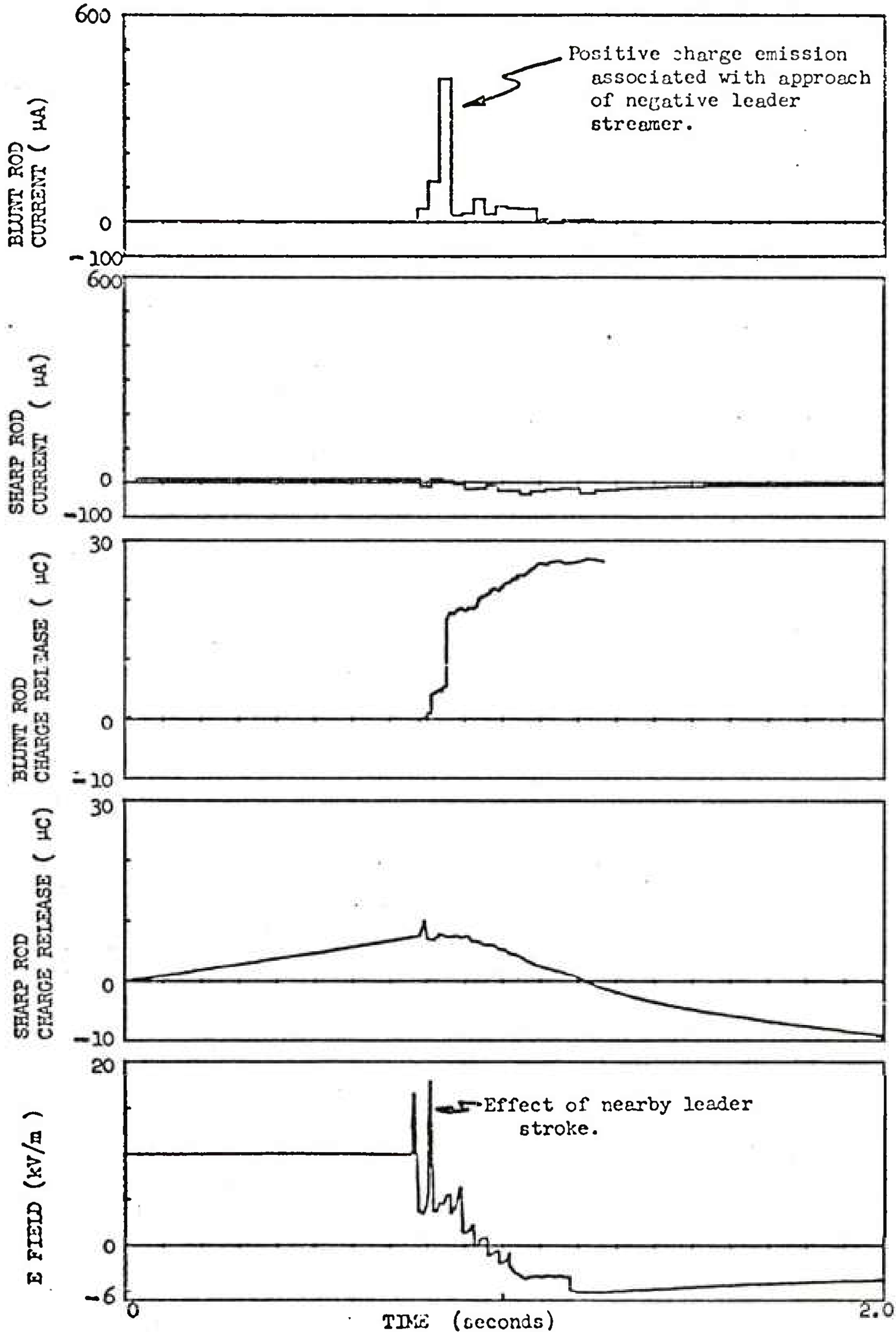


Figure 4

LIGHTNING WITHIN 500 m at 1142 MST ,18 Aug 1974 (74 230)



leader, it then typically emitted large bursts of positive charge. During the study neither of the rods were ever struck by lightning but the blunt rod appeared to continue the emission of positive charge even after the lightning had made contact with the earth and the local direction of the field reversed as the return stroke progressed. Since breakdown processes precede in very short intervals of time, with characteristic times of the order of microseconds, our data are severely limited by the lack of time resolution and only the gross net features can be interpreted. Under these limitations our results indicate that the sharpened rod usually acted to protect itself by emitting ions whenever the electric field exceeded a breakdown threshold. The blunt rod, on the other hand, emitted ions with great difficulty. External increases in the electric field therefore were not limited by the emission of ions around the blunt rod as it was the sharp rod; the fields around the blunt rod often increased to such large values that when breakdown did occur at the blunt rod a positive streamer could propagate for appreciable distances away from the blunt rod. It thus appears to us that there is a significant difference in the response of a sharp rod from that of a blunt rod during the development of a lightning discharge.

MODELING EXPERIMENTS

In an effort to surmount the experimental difficulties, Mr. Standler and I undertook a numerical calculation of the potentials in electric fields around conductors. Solutions of LaPlace's equation around a cylindrical rod projecting up from a flat, conducting plane are not readily available but potential functions for prolate half ellipsoids are well known (Symthe, 1950). After the onset of point discharge, the release of ions requires the use of Poisson's equation. The zone of demarcation between emission and passivity introduces a discontinuity into the relation and makes things difficult. To avoid the decisions about where point discharge begins around the tip and what the effect of the point discharge ions will be on the electric field in the nondischarging region, we selected a cylindrical geometry in which we studied an elevated horizontal wire around which point discharge could develop uniformly. We mapped this array into cylinder coordinates and wrapped a concentric outer cylinder around the central wire. The field at the central conductor was made to vary in the same manner as it would occur in a vertically descending lightning streamer approach to the equivalent elevated horizontal wire above a plane. When the field strength at the central wire exceeded the local breakdown value, point discharge ions were emitted and transported instantaneously as by streamers out to a point where the radial electric field was no longer strong enough for a streamer to propagate. Thereafter the ions moved under the influence of the electric field at velocities determined by the local field strength and their mobility. The distribution of electric fields in this system was then calculated as a function of distance from the center of the wire and of time as the environmental electric field intensified nonlinearly with the approach of the

simulated lightning streamer. Results of these calculations are shown in Figures 6 and 7.

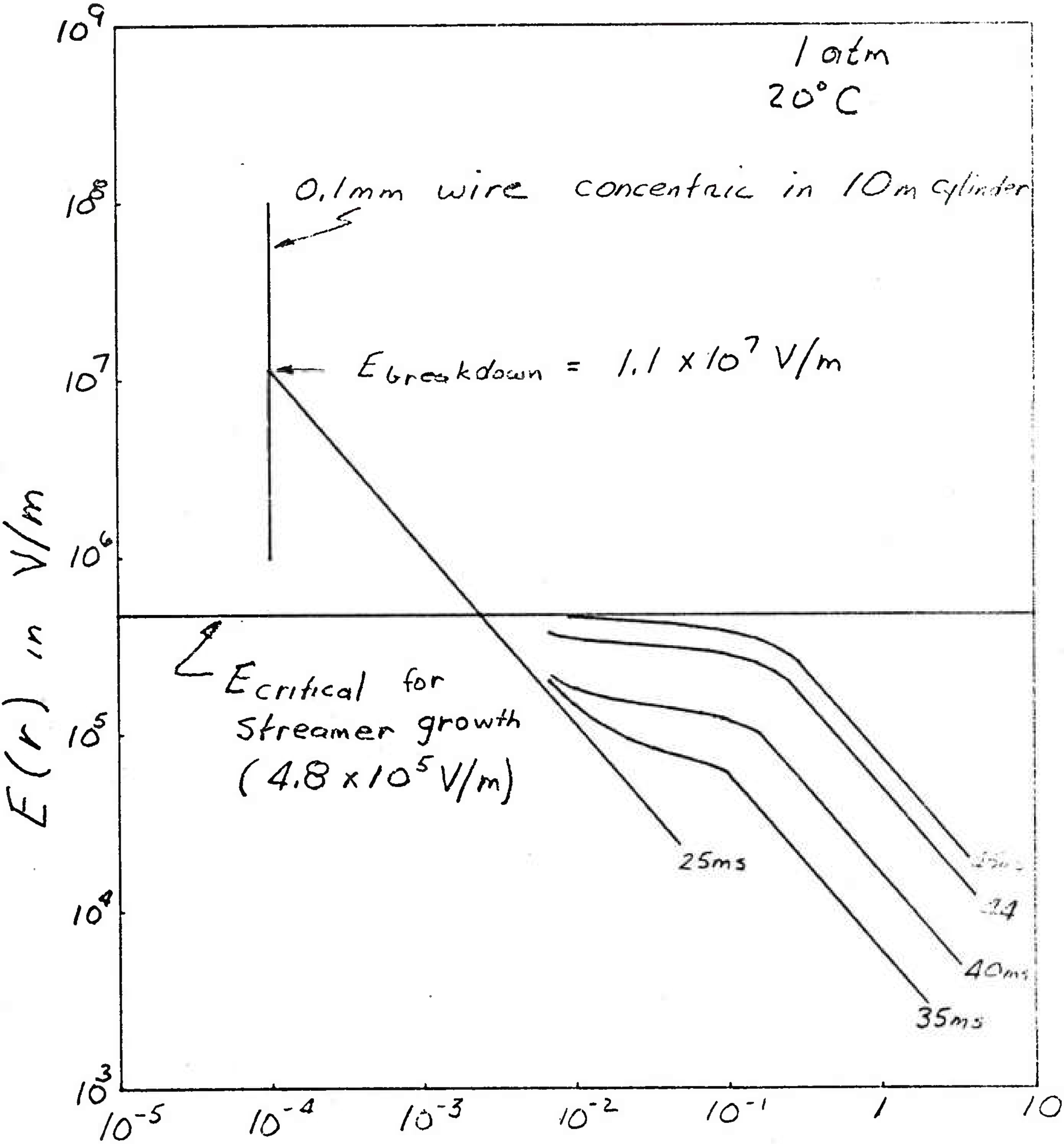
We found that in this model the electric fields would intensify so that 'return strokes' could be induced from central conductors of all radii. The significant difference is that the easy emission of point discharge from small radius wires allowed much of the increased potential difference to take place over emitted charges. Around the equivalent of a blunt wire no charge emission occurred until the ambient electric field had become so intense that when breakdown did occur the strength of the electric field everywhere was sufficient for a streamer to propagate from a central conductor and continue. The catastrophic breakdown from the blunt wire occurred significantly earlier than from the sharp wire by one or two milliseconds.

Our model therefore tends to support our experimental results: Sharp conductors protect themselves by the easy emission of charge whereas blunt rods in the vicinity may be passive until the field becomes very intense at which time they become the preferred candidates to supply the return streamer. From these results it appears that the curvature of the tip of the lightning rod may affect the functioning of the rod for lightning protection. Sharp rods probably will protect themselves by the emission of ions but an approaching streamer, however, may increase the electric field so greatly that some other object in the vicinity supplies the up-going streamer to meet the oncoming discharge and thus participates in the discharge. In this case the sharp rod would fail to serve as a generally useful protective device.

Our prescription then for lightning protection is that the object to be protected might well be covered with easy ion emitters, however, preferred paths to ground in the form of blunt lightning rods should be provided in the vicinity. From our model, if the entire surface beneath a thunderstorm were covered with sharp points and the generating ability of the thunderstorm were able to cause breakdown resulting in streamers approaching the earth, a lightning stroke to a sharp point could still be possible if the rate of increase of field strength were fast enough. The difference between the sharp and the blunt rod is merely a difference in two rates; the presence of a sharp point alone is no guarantee that the point cannot be hit.

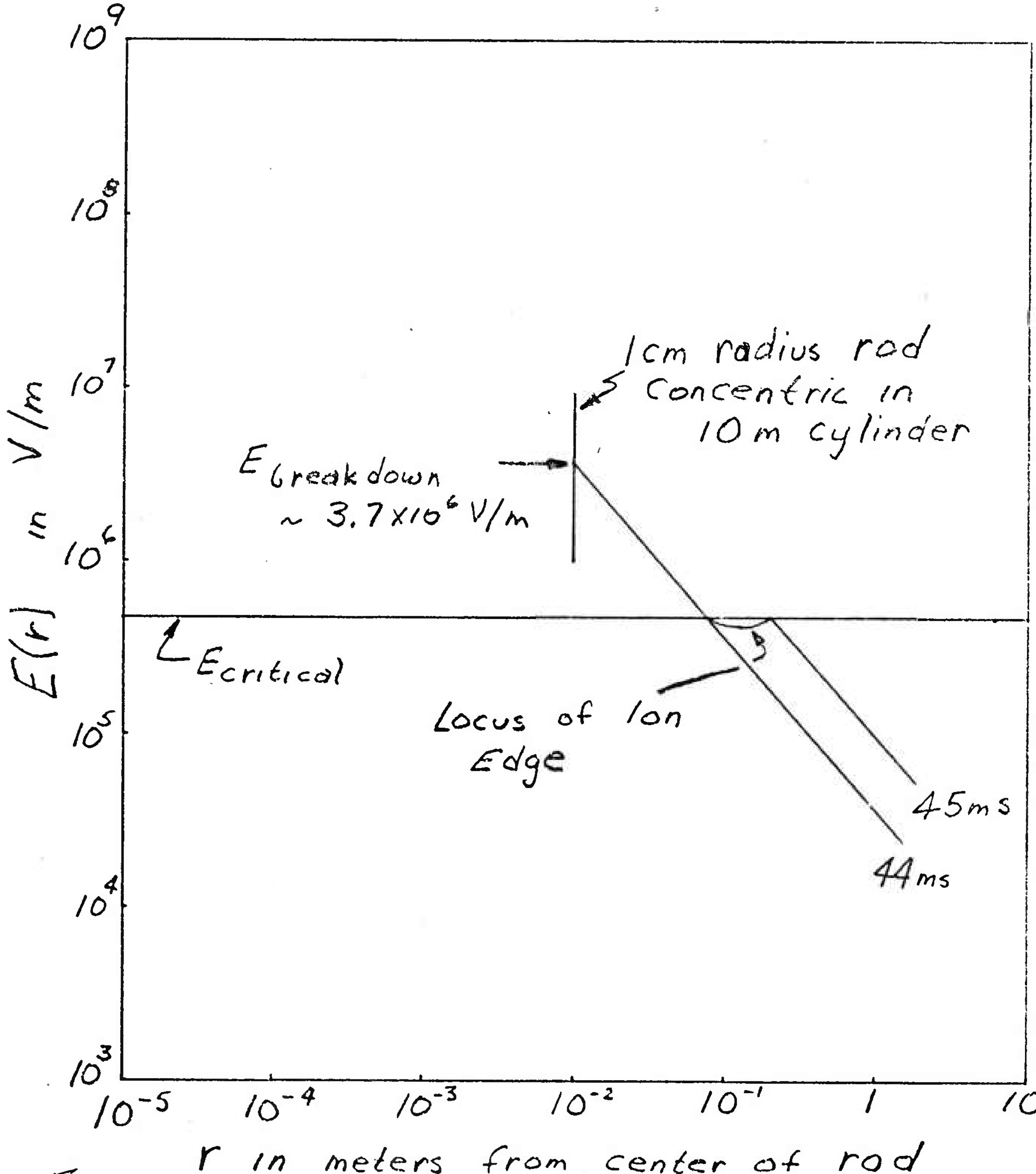
CONCLUDING REMARKS

Departing from the topic selected for me I do wish to register a protest. About five years ago a number of us suggested some techniques in measurements to NASA that might be used to aid in the lightning protection problem. Relatively few of these have been adopted but we have been called down repeatedly to evaluate and apparently to ratify NASA's use of the so-called lightning dissipation array of barbed wire. We have


1 atm
20°C
0.1mm wire concentric in 10m cylinder
E breakdown = 1.1 x 10^7 V/m
E critical for streamer growth (4.8 x 10^5 V/m)
25ms
40ms
35ms
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^-5
10^-4
10^-3
10^-2
10^-1
1
10
E(r) in V/m
r in meters from wire center

119

Figure 6



1cm radius rod
Concentric in
10 m cylinder
E breakdown
~ 3.7x10^6 V/m
E critical
Locus of Ion
Edge
45ms
44ms
E(r) in V/m
r in meters from center of rod

Figure 7

been trapped today into another discussion of a proprietary product which appears to be nothing more than a reinvention of Franklin's lightning rod.

As many people know, the lightning rod was invented after Franklin discovered the ability of a point, subjected to an intense electric field, to make the surrounding air into a conductor of electricity. In about 1750 he suggested that perhaps this effect could be used "to steal the electric fire away from thunderclouds" and thus prevent the development of lightning discharges. Unfortunately for us, his first use of this technique was not recorded but there must have been some interesting results for he speedily suggested another use of the lightning rod: If the exposed and sharpened point did not prevent the lightning from occurring, at least it could provide a preferential path to ground around the object to be protected.

Thus far Mr. Carpenter of Lightning Elimination Associates is still at Franklin's first stage recommending that lightning can be dissipated before it strikes. Since Franklin's results and now our own indicate that sharpened rods may protect themselves but not protect objects in the vicinity, the dissipation array is not sufficient for lightning protection. When discussions of other functions of the sharpened points come up, Mr. Carpenter says effectively that it is up to the experts to explain this business, that his people don't know how the rod works. I agree with him; they don't know what they are doing. The idea that a side-looking array of nails on a top of a mast is required to protect against discharge from coming in from the side reveals lack of comprehension of what is involved. Similarly, the right angles in the ground leads indicate a lack of knowledge of the impedance created to the transient flows of large currents. We made a proposal to Kennedy Space Center for some improved approaches to the lightning protection problem. Instead we must again listen to a further discussion of a proprietary product whose development is still at the level of Franklin's first speculations. I am unhappy about listening to all of this again, at listening to poorly designed protection schemes that cost a great deal of money and are poorly instrumented. It seems to me that rather than discussing a proprietary device that NASA should be asking lightning specialists gathered here today for a series of properly designed studies to improve the protection of very tall towers.

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THEORETICAL INVESTIGATIONS OF ELECTROSTATIC FIELDS AND CORONA AROUND TOWER STRUCTURES

by

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November 6, 1975

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This study was performed to investigate the claims made for the effect of the space charge given off by the dissipation arrays in the "shielding" against lightning strikes. The problem of corona currents is an extremely difficult one to treat theoretically with many factors like point geometry, varying potentials and ion mobility entering into the picture. The wind greatly influences the corona discharge, and relationships are worked out by Chapman [(1)], and the space charge modifying the fields directly around the points exerts a predominating effect on the magnitude of the corona currents.

However, our main interest was not to calculate the actual current values but to find the extent of the volume around various structures over which a space charge cloud could exist, and more limited even, to define a region equal to or greater than the largest possible space charge volume. Hence, it was sufficient to examine from sharp and blunt points and of the electric fields influencing the corona under static field conditions, from which then conclusions could be drawn about dynamically changing situations.

Equations

In the theoretical calculations the tower structures were approximated by prolate spheroids, which bear good resemblance to the overall shape and are convenient for mathematical treatment. A uniform ambient electric field was assumed parallel to the vertical axis of the structures, and the structures were considered to be at ground potential. For these conditions Laplace's electric field equations were solved in elliptical or prolate spheroidal coordinates as discussed in references (2) and (3), to give the potential and potential gradient.

The resulting equation for the potential as a function of the elliptical coordinate ξ with major and minor half axes a and b is,

$$\varphi = \varphi_0 + (\varphi_s - \varphi_0)\frac{\displaystyle\int_\xi^\infty \frac{d\xi}{(\xi + a^2)^{3/2}(\xi + b^2)}}{\displaystyle\int_0^\infty \frac{d\xi}{(\xi + a^2)^{3/2}(\xi + b^2)}} = \varphi_0 + (\varphi_s - \varphi_0)\frac{I_1}{I_2}$$

The potential at the surface $\varphi_s = 0$, because the conducting ellipsoid is grounded, and the potential at height h in the unperturbed parallel field E_0 is $\varphi_0 = -E_0 h$.

$$\varphi = -E_0 h \left(1 - \frac{I_1}{I_2}\right)$$

The vertical and horizontal components of the electric field are,

$$E_V = -\frac{\partial \varphi}{\partial h} = E_0 \left(1 - \frac{I_1}{I_2}\right) - \frac{E_0 h}{I_2} \frac{\partial \xi}{\partial h} \frac{\partial I_1}{\partial \xi}$$

$$E_H = -\frac{\partial \varphi}{\partial r} = -\frac{E_0 h}{I_2} \frac{\partial \xi}{\partial r} \frac{\partial I_1}{\partial \xi}$$

The equation of the ellipsoid,

$$\frac{x^2}{\xi + a^2} + \frac{y^2}{\xi + b^2} + \frac{z^2}{\xi + c^2} = 1$$

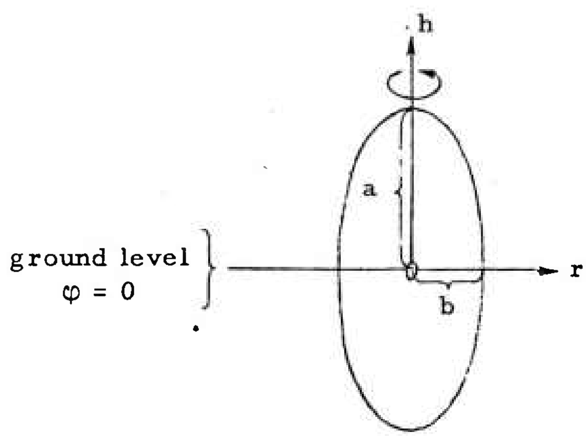
is simplified for the symmetrical case of the prolate spheroid, where the semimajor axis is a, the two semiminor axes b = c, the radial coordinate is the horizontal distance from the center of the ellipsoid $r^2 = y^2 + z^2$, and the height coordinate $h = x$;

$$\frac{h^2}{\xi + a^2} + \frac{r^2}{\xi + b^2} = 1 \text{ and } \xi = f(h, r)$$

The partial derivatives are,

$$\frac{\partial \xi}{\partial h} = \frac{2h\ (\xi + b^2)}{2\xi + a^2 + b^2 - r^2 - h^2}$$

$$\frac{\partial \xi}{\partial r} = \frac{2r\ (\xi + a^2)}{2\xi + a^2 + b^2 - r^2 - h^2}$$



Setting $c = a^2 - b^2$, the evaluation of the integrals yields,

$$I_1 = -\frac{2}{c^2\sqrt{\xi + a^2}} - \frac{1}{c^3} \ln \frac{\sqrt{\xi + a^2} - c}{\sqrt{\xi + a^2} + c}$$

$$I_2 = -\frac{2}{ac^2} - \frac{1}{c^3} \ln \frac{a - c}{a + c}$$

$$\frac{\partial I_1}{\partial \xi} = -\frac{1}{(\xi + a^2)^{3/2}(\xi + b)^2}$$

Hence the equations for the potential φ, the vertical component E_V and the horizontal component E_H of the electric field around a conducted grounded prolate spheroid in a parallel electric field E_0 are as follows:

$$\varphi(h, r) = \varphi\left[h, \xi(h, r)\right] = -E_0 h \left(1 - \frac{\dfrac{2}{\sqrt{\xi + a^2}} + \dfrac{1}{c} \ln \dfrac{\sqrt{\xi + a^2} - c}{\sqrt{\xi + a^2} + c}}{\dfrac{2}{a} + \dfrac{1}{c} \ln \dfrac{a - c}{a + c}}\right)$$

$$E_V = -\frac{\varphi}{h} - \frac{2 E_0 h^2}{\left(\dfrac{2}{ac^2} + \dfrac{1}{c^3} \ln \dfrac{a-c}{a+c}\right)(\xi + a^2)^{3/2}(2\xi + a^2 + b^2 - r^2 - h^2)}$$

$$E_H = -\frac{2 E_0 hr}{\left(\dfrac{2}{ac^2} + \dfrac{1}{c^3} \ln \dfrac{a-c}{a+c}\right)\sqrt{\xi + a^2}\,(\xi + b^2)(2\xi + a^2 + b^2 - r^2 - h^2)}$$

These equations were programmed and a variety of conditions were computed and plotted.

Results

Figure 1 shows 2 cases of equipotential lines around 30 m high towers of different diameter. Fair weather field conditions of 200 V/m are assumed, however, the equipotential line distribution gives the general picture for any value of the ambient field, requiring only a change in scale. The left plot is of a pointed tower having a 3.3 cm radius of curvature and shows the equipotential lines just around the tower are greatly modified from the parallel field situation. It is striking how closely the lines follow the tower along the vertical structure and how

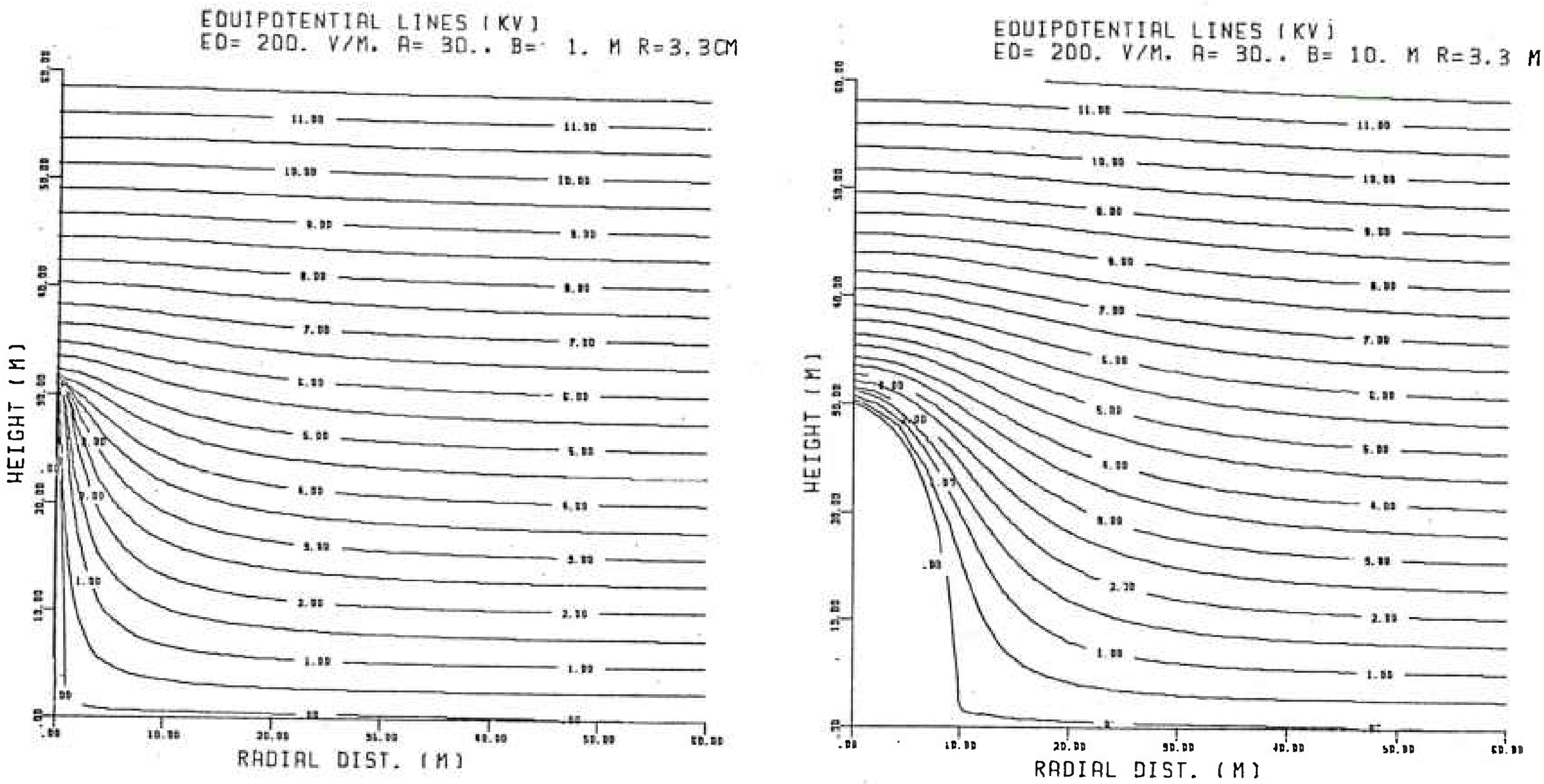


Figure 1. Equipotential Lines around Pointed and Blunt Towers

they are concentrated just around the top. But just a short distance away from the tower the parallel field situation is regained. Around the blunt structure with 3.3 m radius of curvature, the picture looks quite different. The equipotential lines are not as closely gathered around the blunt structure as they are around the pointed one, but the field is effected more at greater distances as is apparent by the line concentration. This implies that under appropriate high fields corona ionization occurs only in the immediate vicinity of the sharp point, but over a larger volume around the blunt point.

The field lines run perpendicular to the equipotential lines as represented in Figure 2. The collection area is marked off, for which the field lines terminate on the tower. If a lightning leader was coming down, and the phenomena was assumed very weak, then theoretically it would follow one of the field lines. But of course the high charge carried in a downcoming leader modifies the entire field line pattern; hence the collection area cannot be considered a lightning cone of attraction. The collection area is however, a useful piece of data indicating the distance that structures should be spaced apart in the field to be electrically uneffected by each other. This distance is quite different for the two structures, it is roughly half the height for the pointed tower and equal to theheight for the blunt structure.

The direction and magnitude of the electric field at any point around the tower determines the movement of existing ions, if winds are neglected. Figure 3 is an instantaneous picture of the speed and direction of small ions indicated by the arrows, based on a mean small ion mobility of 1.5×10^{-4} m/sec at 1 V/m. At the tip of the pointed structure the ions obtain considerable speed, 300 times as high as in the ambient field, whereas atop the large round structure the ion speed is only about 3 times that obtained in the unperturbed field. Above the central part of the round structure the arrows are of about constant length and vary only little in direction, which implies a nearly constant and parallel field over an area of at least a few square meters.

Placing now a 3 cm high point of 1/10 mm radius of curvature on top of this 30 m round structure, would yield a similar picture as might be found in the center of a barbed wire dissipation array. Using the information that the field can be considered constant and enhanced by a factor of 3, the situation can be paralleled to a 3 cm sharp point at ground level in a field 3 times as high as normal. Assuming storm conditions of -10,000 V/m then yields the ambient field at -30,000 V/m, and the equipotential lines are shown in Figure 4. The enhancement at the tip of the point is 370. Comparing this data with a simple sharp spike of the same radius of curvature as the 3 cm point placed at ground level in the stormy field of -10,000 V/m, it is found that the spike would only have to be 12 cm high to give the same field enhancement of 370. Hence, neglecting wind, the corona given off by a 3 cm point atop a 30 m blunt structure is comparable with that from a 12 cm point at ground level. This suggests that the center portion of an elevated dissipation array gives off very little corona.

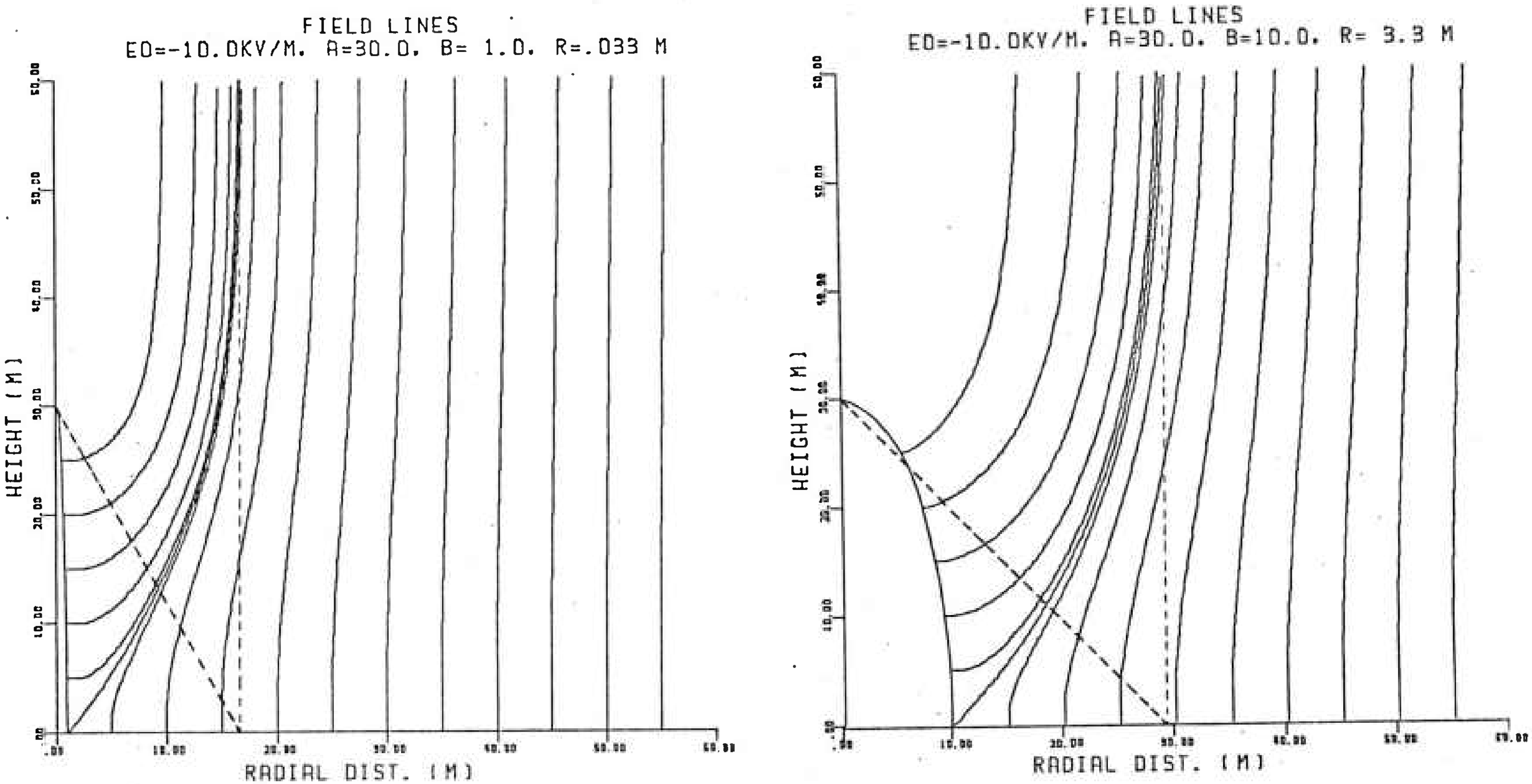


Figure 2. Electric Field Lines and Collection Area

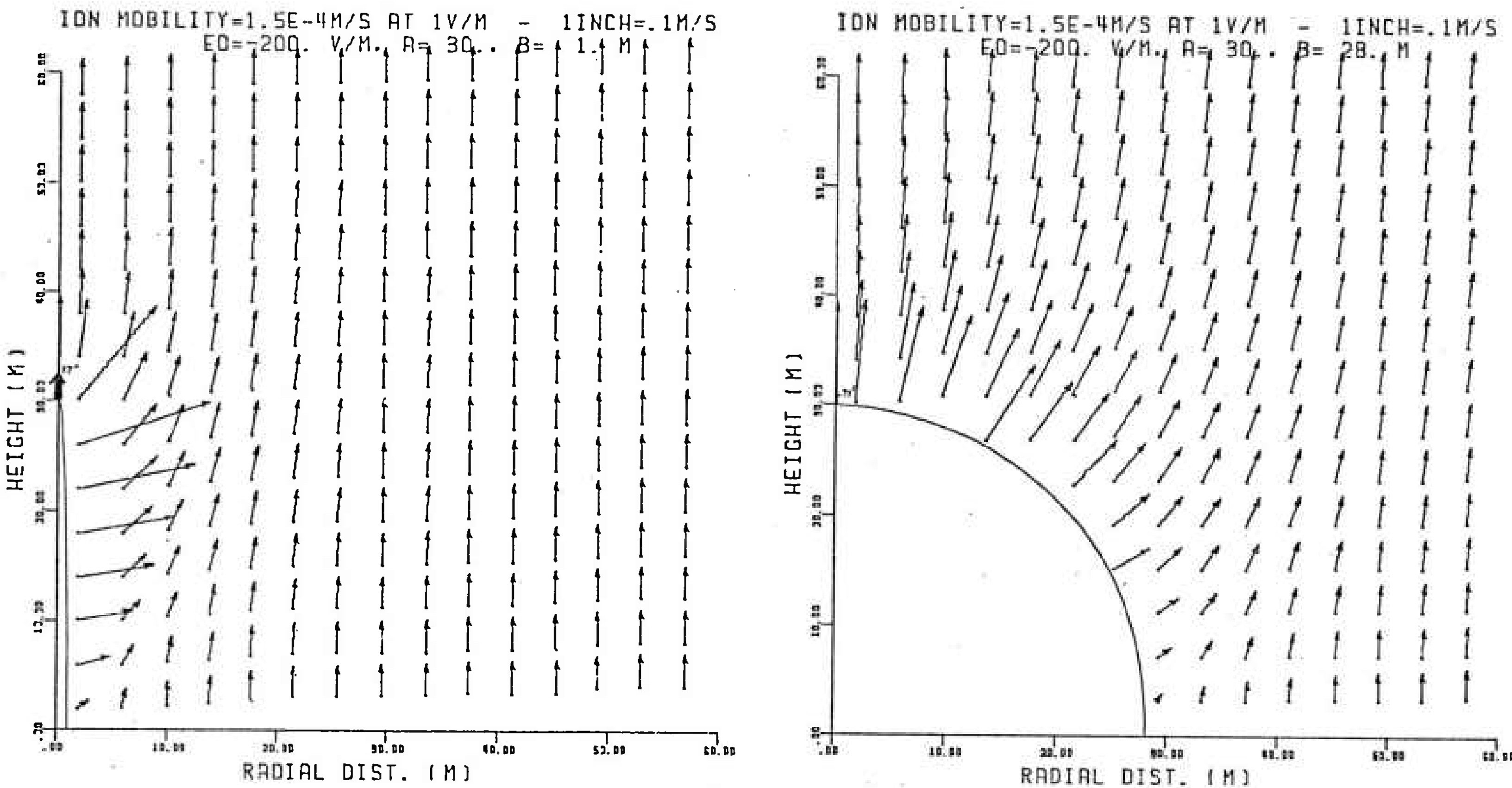


Figure 3. Instantaneous Picture of the Ion Movement

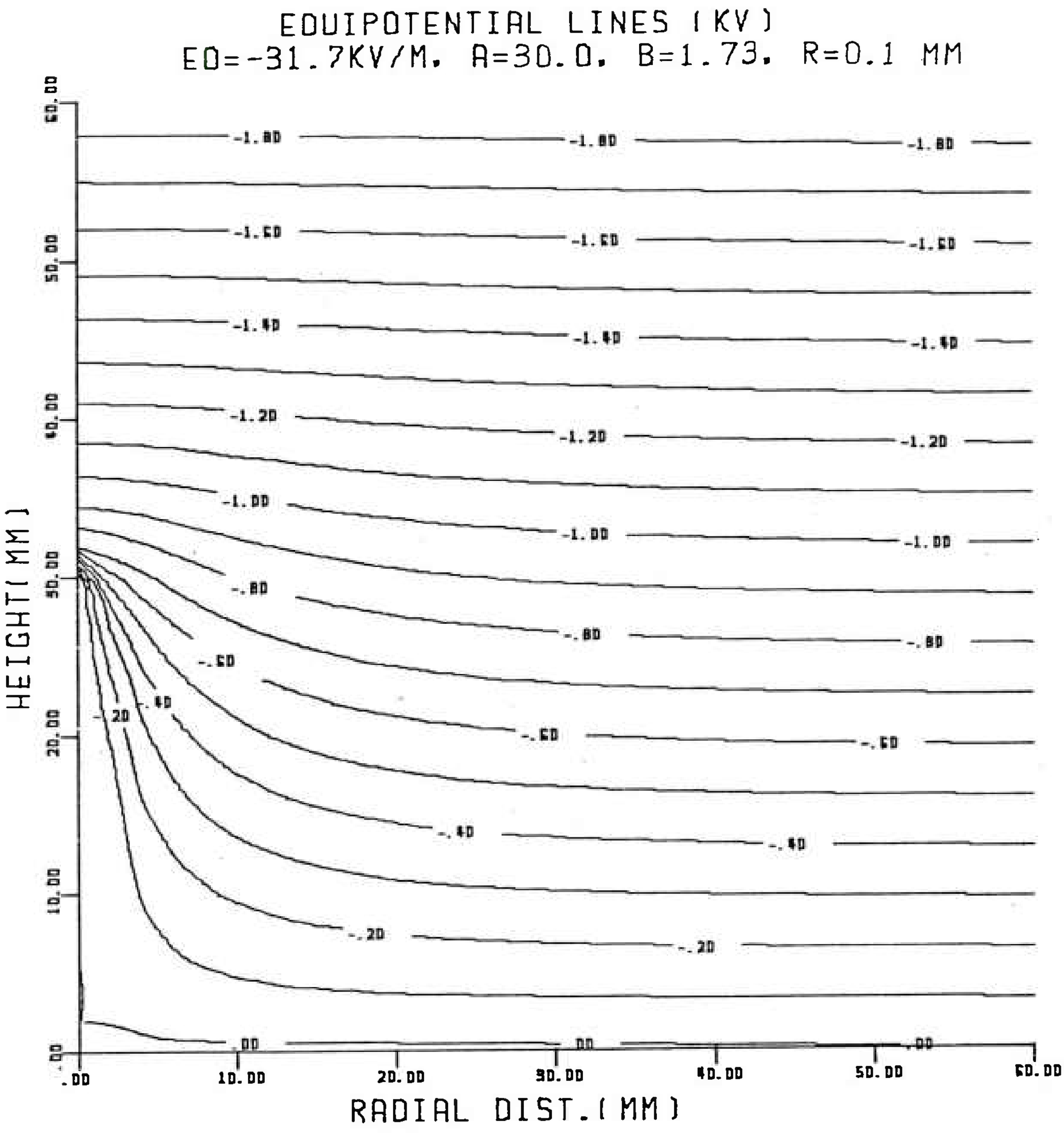


Figure 4. Equipotential Lines around a Sharp Point on Top of a Rounded Structure

In Figure 5 the effects of wind on corona are studied. In this approach only horizontal winds are considered neglecting any updrafts as might exist before and during thunderstorms. The last 2 m of a pointed 30 m high tower are plotted in a storm field of -10,000 V/m. Ionization along the tower surface will take place only where the field is enhanced to values greater than the breakdown potential gradient which is roughly assumed at 1 million V/m.

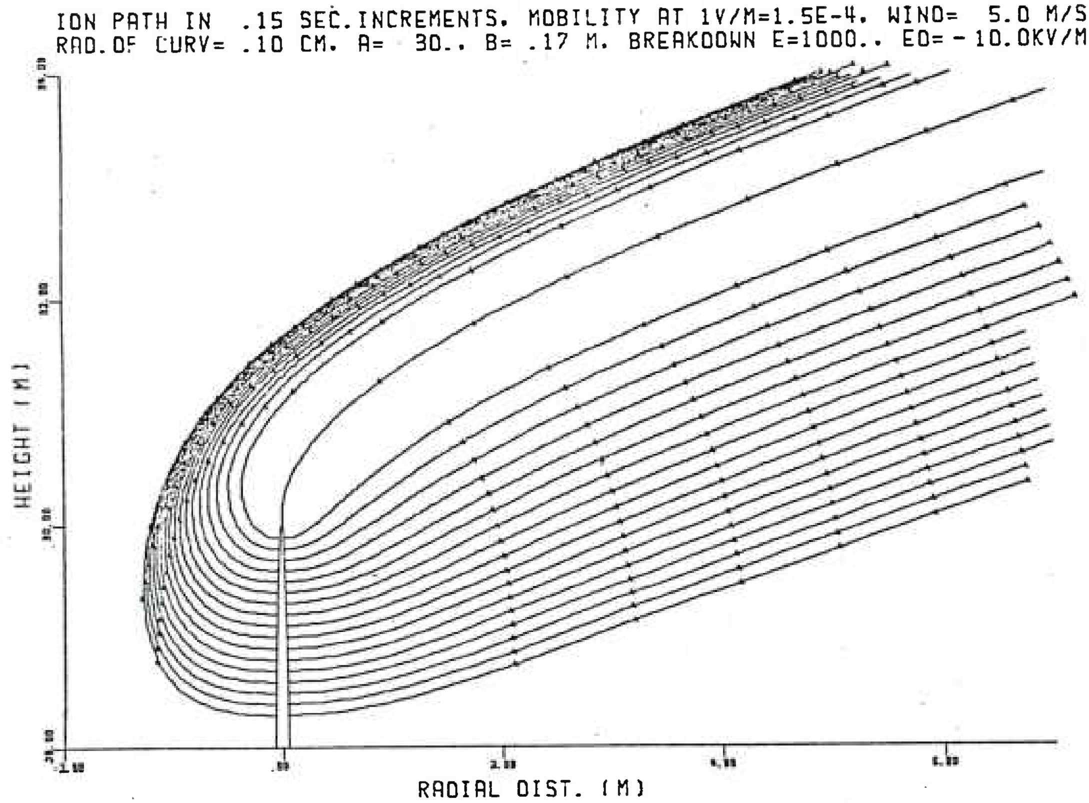
First, to determine the outermost boundary of a possible space charge cloud, consider the simple picture where space charge does not effect the field. Two cases for winds of 5 and 15 m/sec are shown. Under the effect of the field the ions move upward and out to the sides, and wind adds an extra horizontal component to their movement, creating a sort of concentrated line charge as the ions travel around the tower. The ion speed right at the tower is very high and drops off rapidly with distance. In the first case the markings along the ion path are reached at 150 msec intervals, in the second case at 50 msec intervals. The ions do not travel far into the wind under either situation, at most 1.25 m.

The situation can now be considered with space charge limiting. Once corona is formed and starts moving out from the tower, its charge would reduce the field around the tower to below the breakdown potential gradient, and corona discharge would cease. Within a fraction of a second the wind would blow the charge clear of the tower, exposing it again to high fields, and ions would be formed again etc. This causes the corona currents to be given off in bursts, as first observed by Trichel in 1938 (4). When each layer of ions is moving out from the tower, the wind is the dominating effect, since the field is reduced, and the top graph would under this dynamic situation be modified to look more like the one on the bottom.

Hence, under any condition ions will not escape the maximum boundaries shown in the top graph. The ion cloud would only expand less than 1 m into the wind at the very top section of the tower that goes into corona, and it would move in a near horizontal trail away from the tower much like the smoke of a factory chimney, where the upward motion is comparatively small. A corona trail like this could not possibly reach the charge center of an overhead cloud, nor would it yield a protective shield against lightning strikes to the tower.

More detail on how far the ions move into the wind is presented in Figure 6. Only the radial component of the ion movement is considered for values of horizontal wind. Double logarithmic scales are utilized to show the situation close to the tower and also at some distance away. Starting from the tower top upwards, conditions were examined 1/10 mm, 1 mm, 1 cm, 10 cm, 1 m above the tower; the same was done going down from the top and going outward from the center. The discontinuity in the center of the graph, where the data sets are merged, is insignificant. Contour lines are drawn for different wind speeds from 5 - 25 m/sec. The enclosed area represents the only region around the tower where ions have a resultant horizontal velocity component that allows them to move into the wind.

The exposure factors help determine how soon and out to what distance a tower will go into corona. Figure 7 shows two 30 m high towers with radius of



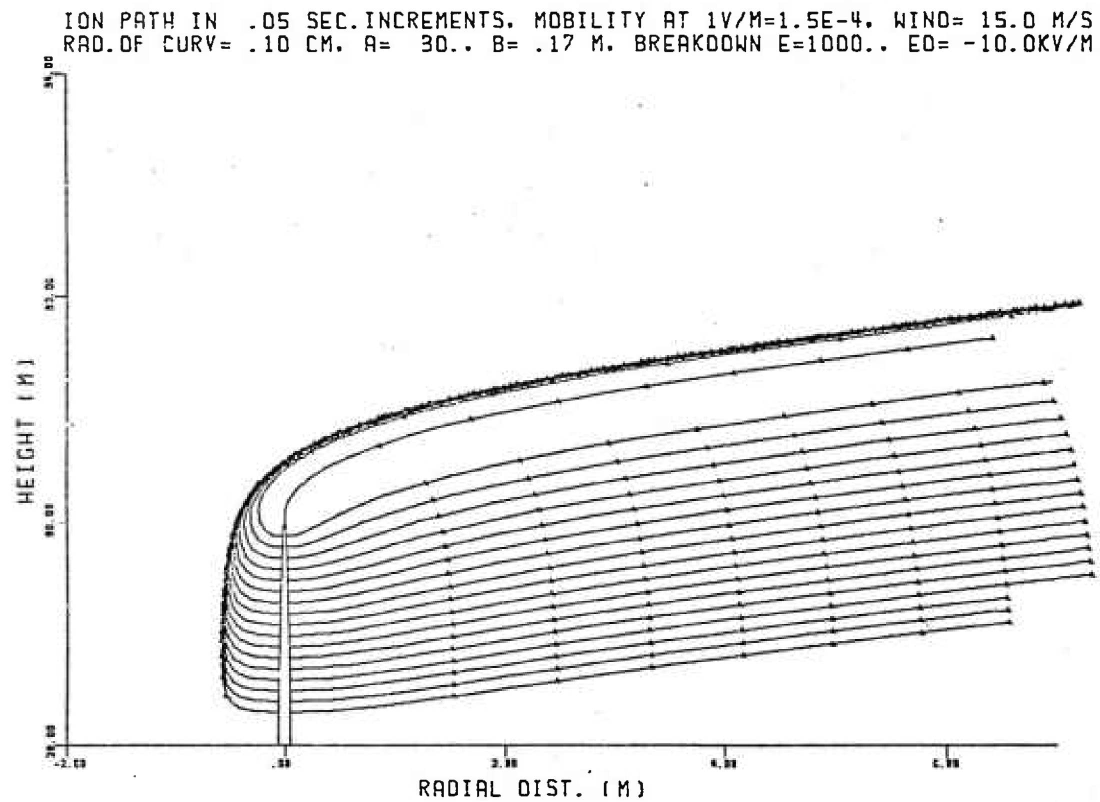


Figure 5. Ion Movement under Horizontal Winds Showing Maximum Boundary of Ion Cloud

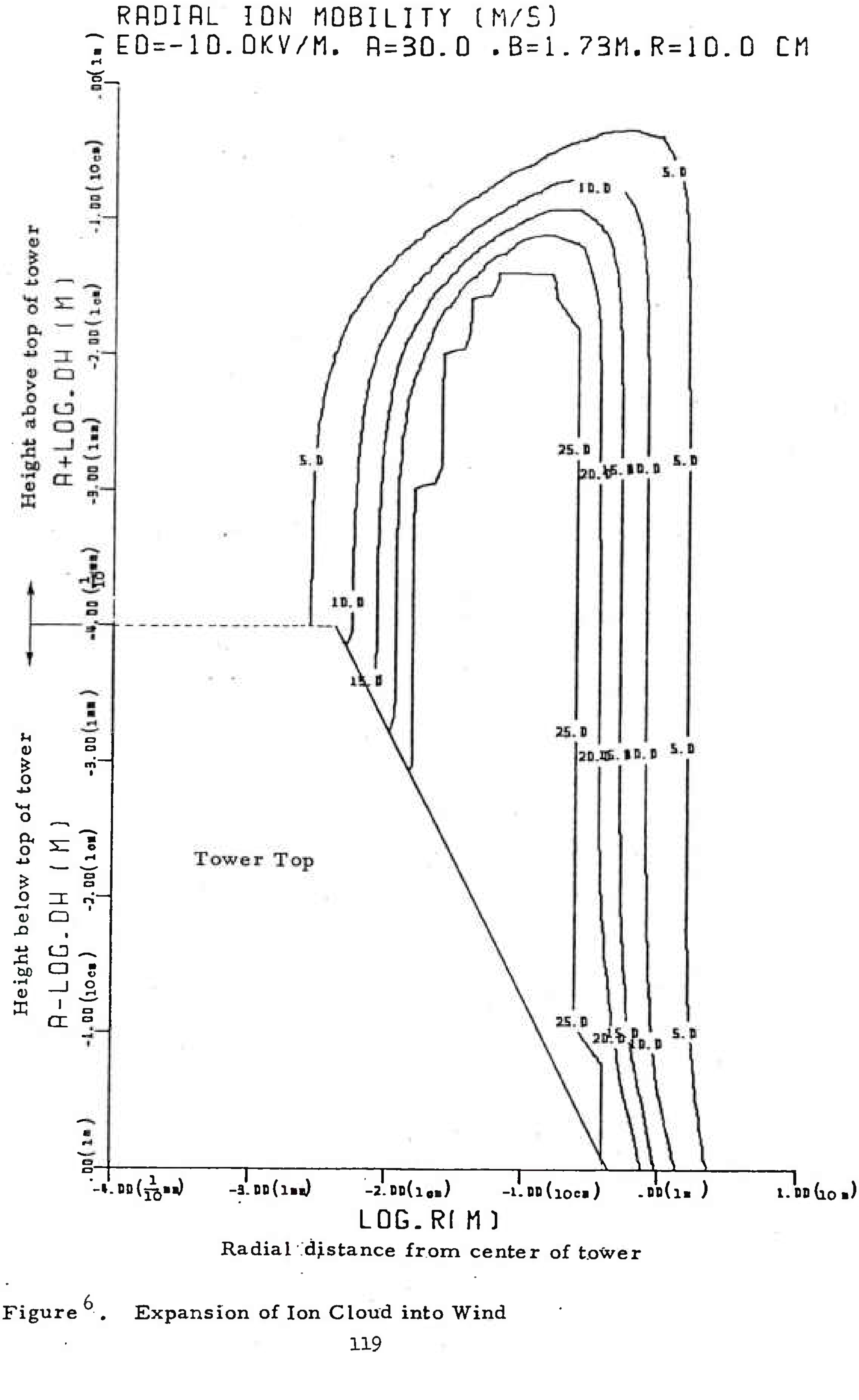


Figure 6. Expansion of Ion Cloud into Wind

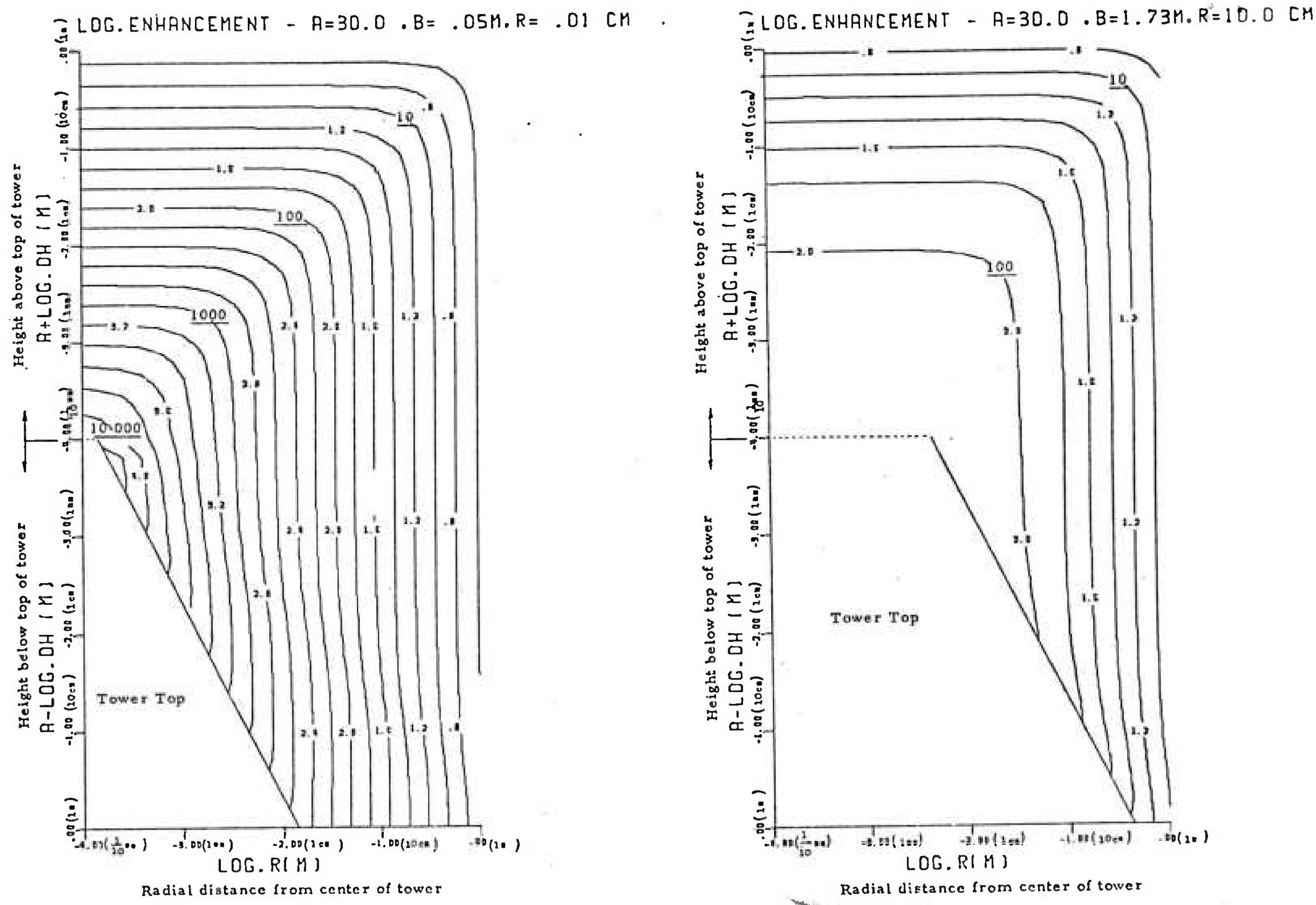


Figure 7. Lines of Equal Value for Exposure Factors around Sharp and Blunt Structures

curvature of 1/10 mm and 10 cm. Lines of equal value were drawn for the exposure factors in an area around the top of the towers, again using double logarithmic scales to show detail near and far. The enhancement at the tip is of the order of 10,000 for the sharp point but only 100 for the blunt point. This means that only fields of the order of 100 V/m are required for the sharp point to be in corona, which is in agreement with our experimental results from a sharp point giving up to 1/4 μ A current in fair weather fields. For the blunt point however, storm conditions of 10,000 V/m are required before corona is given off. It should be noted that the enhancement for the sharp point drops off very rapidly with distance, it is down to a factor of 10 only 30 cm above the tip. The enhancement of the blunt point is larger at these distances and drops down to 10 only at twice this distance, or 60 cm above the top.

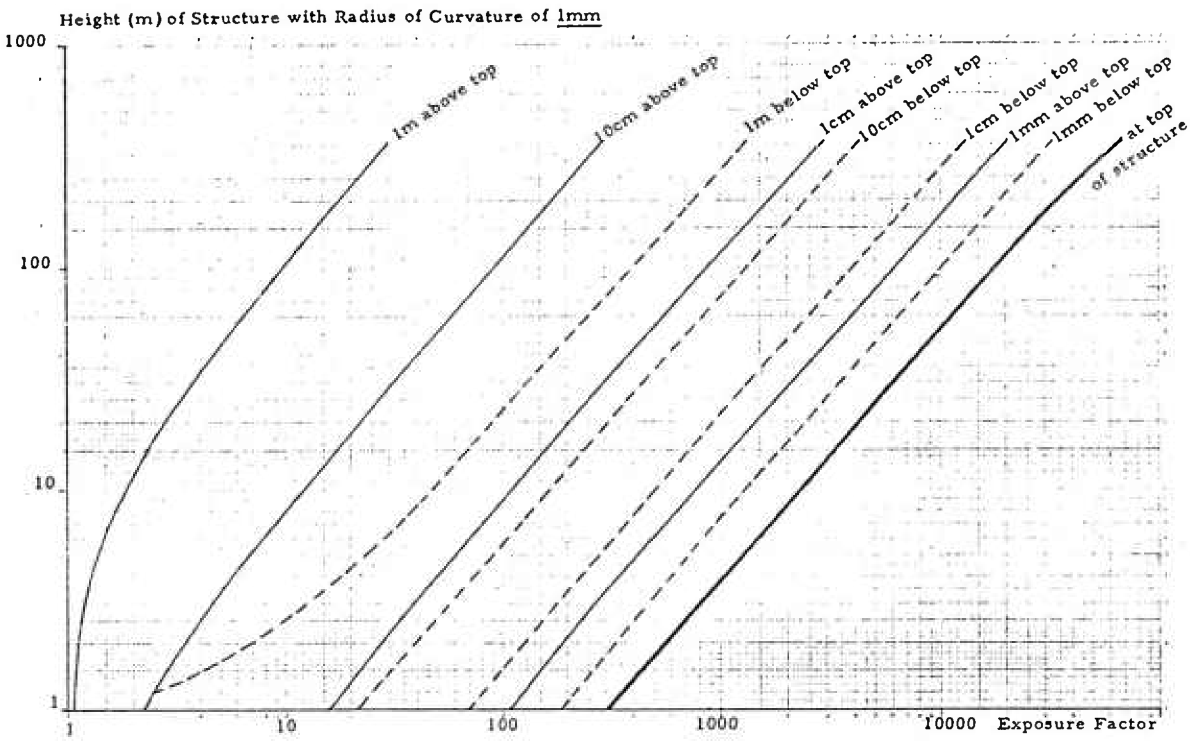
The sharp point goes into corona in low fields and just immediately around the tip, the blunt point goes into corona only in high fields, but out to greater distances from the tower.

In Figure 8 the exposure factors are plotted versus height for 2 values of radius of cuivature, 1 mm and 3.3 cm. This data can be useful in correlating measurements from different heights, or for determining the minimum height of a structure for corona breakdown to occur, given the values for the ambient field and the sharpness of the structure. The think line gives the enhancement relationship at the top of the structure, the solid lines are valid at distances vertically above the structure, and the dashed lines are valid at the edge of the structure below the top.

The overall shape of a dissipation array is that of a blunt top. Hence it may not go into corona until the field reaches very high values, at which time it may go into corona over a greater volume than would a sharp point, and from this argument it could tend to attract lightning. However the effect of the many sharp points and the presence of space charge would modify the picture here and cannot be neglected, but their influence is very difficult to estimate.

Another hypothesis supports the properties of such an array reducing the number of strikes to a very tall structure. In such a situation the upward going leaders, which may be dominant on structures in excess of 600 feet, may be reduced if the overall corona discharge emanates from all the points on the array. This would tend to put the array in a glow situation and reduce the tendency for a glow to arc discharge initiating an upward going leader. Theoretically the idea sounds feasible but in practice it is, no doubt, almost impossible to build an array over which the electric field is uniform at all points on the array. Some reduction in the number of upward leaders may however be possible with careful design. The present tower arrays however would not meet the necessary design qualifications, as the electric field around their extremities would be very large.

In measuring the corona currents given off by dissipation arrays, standard air terminals and similar conductors, one has to consider that the instantaneous measurement of the apparent current cannot be expected to give an



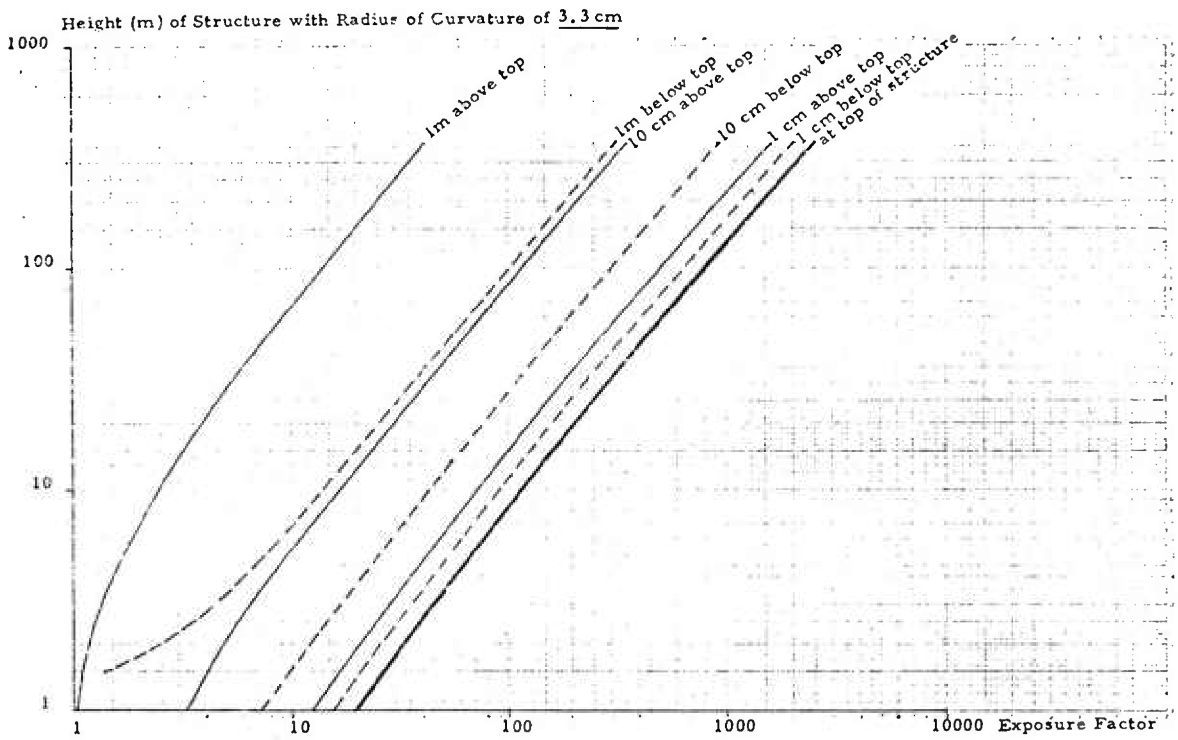


Figure 8 . Exposure Factors at Top of Structures, Vertically above, and below at Side of Structures

accurate value of the true corona current. The sudden changes in the potential gradient give rise to displacement currents which do not involve any charge transfer. These rapid field changes are linked to lightning discharges and give sudden excursions superimposed on the true corona current recordings.

Some theoretical calculations were performed to give an estimate of the size of the displacement current as a function of the tower height, the radius of curvature and of the field change. The displacement current I_d is related to the rate of change in the ambient electric field E_o by

$$I_d = \epsilon_0 \frac{d}{dt} \int E \, dA = \epsilon_0 \frac{d E_0}{dt} \int Enh \; dA,$$

where the integral depends on the shape of the structure, dA is an area element, E is the electric field and Enh is the enhancement both at the surface of the conductor. The tower shape was assumed ellipsoidal and the integration was performed only over the top segment of 5 cm height to reflect the influence of an overhead storm, for which the effect of the change in an assumed parallel field condition on the vertical segments of the tower is extremely small.

In Figure 9 the displacement current is given per unit of time rate of change in the ambient field, increasing in magnitude with the structure height as it goes from 1.5 to 360 m. The displacement current also increases with the radius of curvature, which in effect enlarges the surface area exposed to the field. In Figure 10 the displacement current is plotted against the rate of change in the ambient field for 30 m high structures with both sharp and blunt tops. With Uman's (5) theoretical value for the field change due to a close lightning flash of 180 V/m in 1μ sec, displacement currents of 2 to 7 mA would result. Much larger experimental values of field change are often recorded, by a factor of at least 10 or 100 higher than the theoretical numbers, which would give rise to proportionately larger displacement currents.

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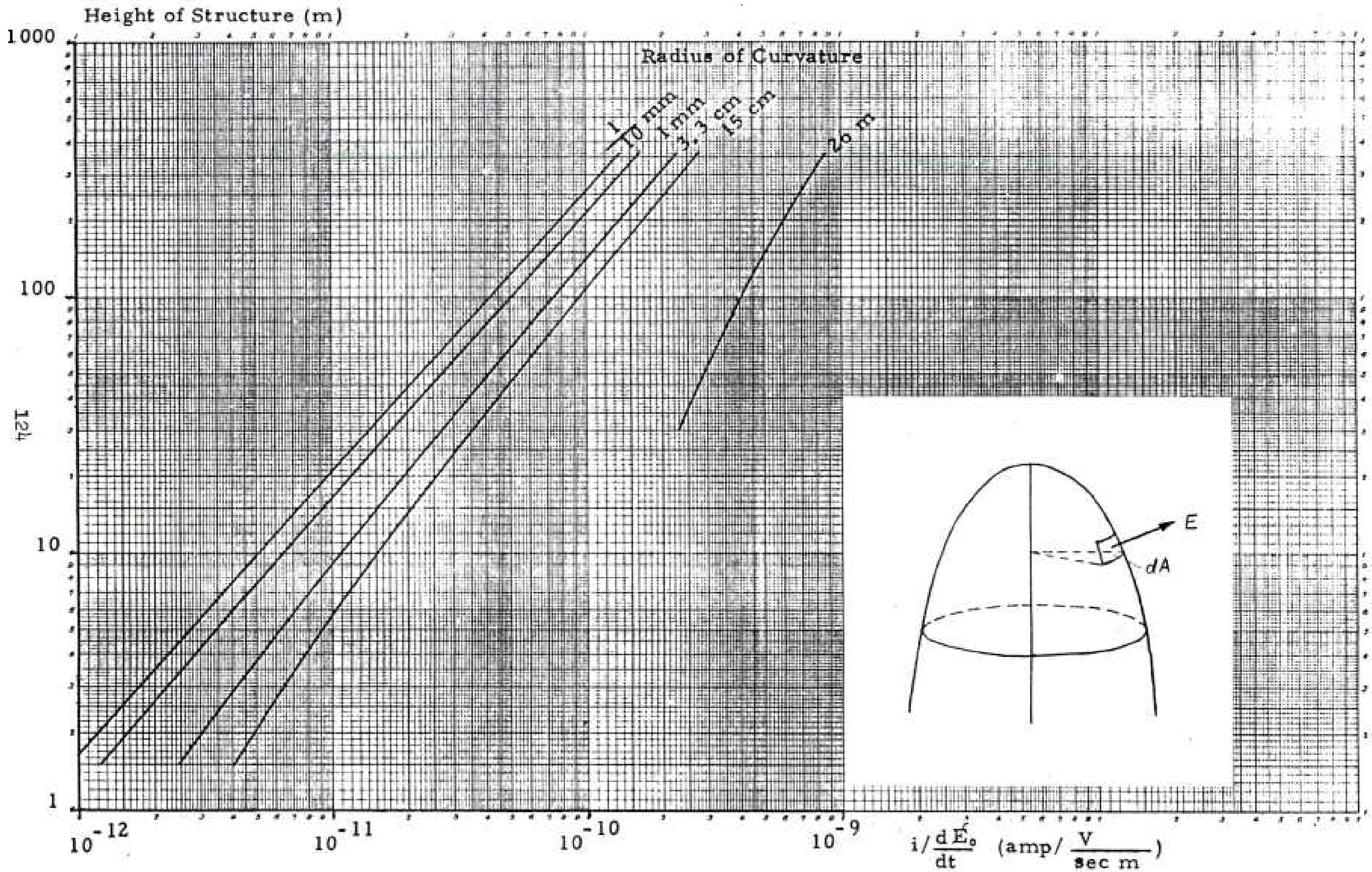

Figure 9 .. Ratios of Displacement Currents and Rate of Change in Ambient Electric Field

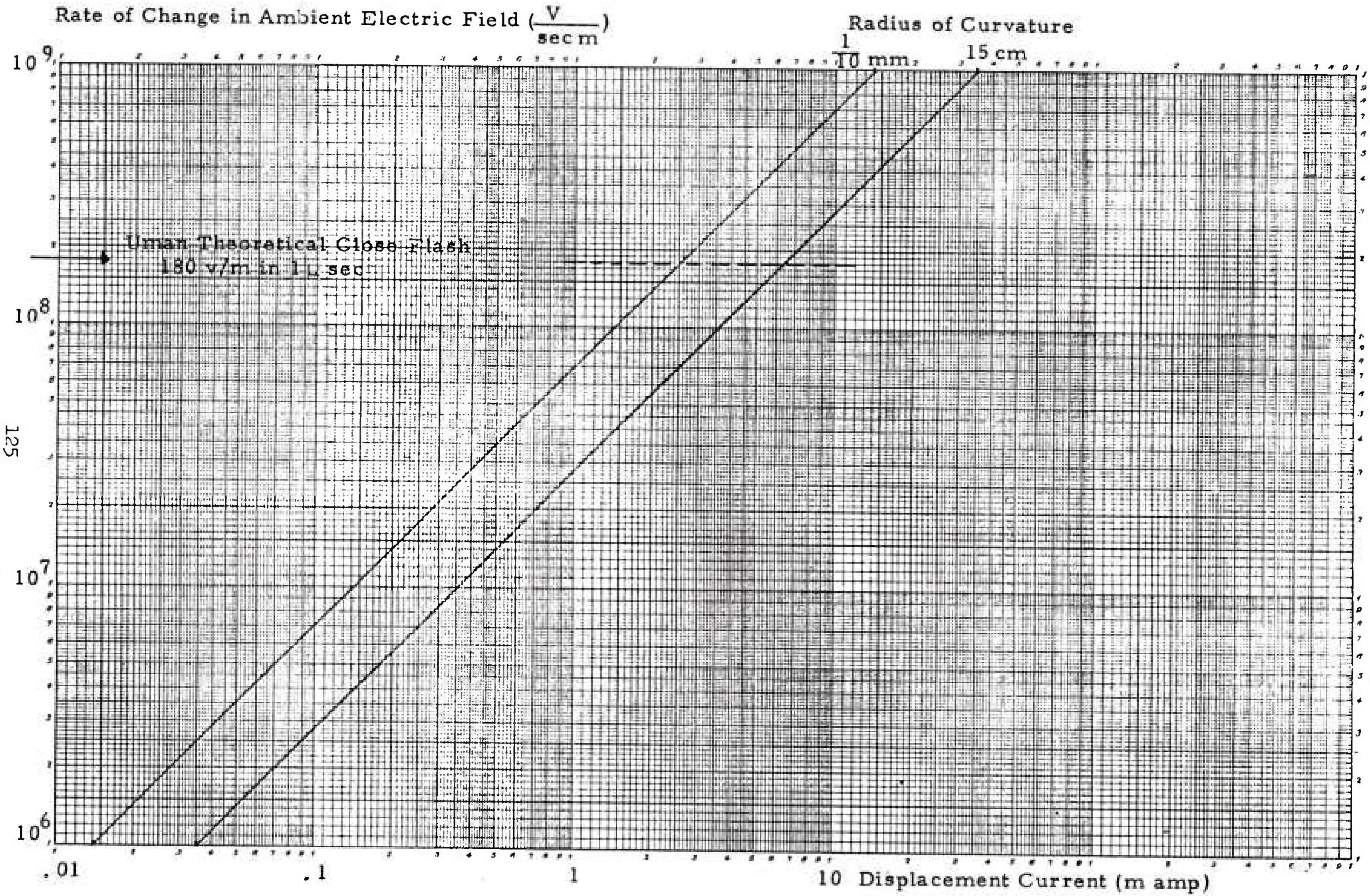

Figure 10. Displacement Currents for 30 m High Structures

MEASUREMENT OF DISSIPATION ARRAY PERFORMANCE AT EGLIN AFB, FLORIDA

by

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of

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November 6, 1975

TABLE OF CONTENTS

MEASUREMENT OF DISSIPATION ARRAY PERFORMANCE AT EGLIN AFB, FLORIDA

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November 2, 1975

Introduction

This is a report on measurements of the performance of several arrays of sharp points installed on elevated structures at Eglin AFB. The arrays were installed by a contractor over the period from 1972-74. It was a matter of primary interest to Eglin AFB and the Atmospheric Science Section of ONR to make atmospheric electrical measurements in order to determine array performance. The possibility of such a system functioning as a current source capable of dissipating the charge in electric storm clouds was a matter of primary concern because it may provide protection to sensitive installations and also produce some other unusual affects in the atmosphere. Therefore an attempt was made to perform measurements that would provide information on these matters. The work was conducted with support of ONR and USAF funds received under ONR Contract No. N00014-67-A-0113-0023, NR 082-229.

Approach and Instrumentation

An effort to measure the performance of arrays placed between 12 and 366.0 m (40 and 1200 ft) above ground was made at two sites on the Eglin AFB, i.e. at C-74 and C-9. At the sled track site, C-74, several types of arrays had been installed as shown in the sketch, Figure 2. After some consideration of what would be possible with available equipment and limitations associated with the site, an attempt to detect an increase in space charge, due to reported dissipation currents up to .15 amps[1], by monitoring the electric field up and down wind from an array seemed reasonable. Computation of the approximate space charge distributed down wind indicates a readily detectable effect by measuring (F), the atmospheric electric field at ground level (this calculation is given in appendix I). The 550.0 m (1800 ft) long array 12 m above ground was one site where the measurements could be made. A 0.61 m x 0.90 m (24" x 36") plate with about 80 points, like 7.5 cm (3") long nails, on a 12 m pole near the CZR bunker was also considered. Therefore, field mills were placed 1.5 m (5 ft) above ground on tripods, as shown in Figure 2. Field mill #3 was placed between mills #1 and #2 with stators flush to the ground surface for one week to make a site determination of the form factor. One would expect a measurable change in (F) between upwind and downwind positions with respect to the array during periods of time when electrical storms were near or over the region. A single point was placed 12 m above ground about 6 m from the plate of points for comparative purposes at the CZR bunker. The prevailing electric storm winds were more often from either the SW or the NE than from any other direction. Therefore, little interference between the single point and the plate would be expected. An attempt was made to

measure the current from the plate of points and from the single point on a continuous basis. It was not possible to measure the current from the 550.0 m long array because of the extensive grounding systems employed. An underground line tied ground rods at each pole to a ground rod at each end of the sled track that went down a depth of 18 m. The sled track ground was also tied to the CZR bunker equipment ground by an underground line.

A field mill was also placed in an opening of the array on the 25.0 m (80 ft) tower at one end of the sled track to detect effects from corona currents on (F). The rate of increase in (F) as a storm approached the site should be considerably less than what may be expected due to the space charge generated by large corona currents from the array. It should be most apparent at the transition between simple point discharge and corona discharge. An attempt was also made to measure the current from about 20 points, an electrically insulated section of the array material mounted 10 cm above and 75 cm on one side of the opening in the array, on the 24 m (80 ft) tower at C-74.

A field mill was placed level with the surface in an opening of the array on the 1200ft(~400 m) tower at C-9 and on the ground 200 m from the tower. An attempt was made to operate several field mills on the ground up and down wind from the tower, but the remoteness of the site and limited A.C. power made this impossible during the time available, Fig. 3.

In the past corona current had been monitored by measuring the voltage across a 10 or 12 ohm in series with the line from the array to ground (the earth). A resistance of this value was preferred because it did not interfere with array performance.

Several arrangements of 741 and 309 op-amp circuits were employed to monitor the voltage across the 10-12 ohm resistors with model AW spring motor 1 ma Esterline-Angus Records. No satisfactory method was found to protect the op-amps from burn-out during intense electric storm activity.

Standard "looking-up" field mills, U of M, Dr. D. Freier design, were employed in all continuous measurements of the electric field. A radioactive probe, with a 20 mc Am_{241}, was also used to map the electric field near towers and also provide a check on form factor determinations for the field mills on tripods.

In the following discussion the potential gradient during fair or fine weather is considered positive and positive ions in the free atmosphere move down towards the earth. The term electric field or field has been used at times for phonetic reasons when the direction of the gradient is not questionable.

A calibration of the field mill used on top of the tower at C-9 was made in our laboratory as a demonstration of response to potential gradients up to 500 KV/m as shown in Fig. 4.

A calibration run of an amplifier used to measure corona current from the array on top of tower at C-9 is shown in Fig. 5. Several of these amplifiers had to be built because a number were destroyed by high input currents at this site. They were made equivalent in sensitivity to within 10% by adjustment of amplifier gain.

Measurements

The dynamic range of electric storm activity is so high that linear response of recording systems requires a series of recorders with overlapping ranges or setting the amplifiers to give a useful pen deflection of limited resolution but not go off scale. The latter was employed in this project with some loss of resolution. In Fig. 6 a set of chart records of a single event is shown: i.e. when (F) is at least 20 times the fair-weather value. Where the pen went off scale, extrapolation is possible to obtain an estimate of the electric fields at each site. The ground surface sloped toward the sled track on each side so that field mill #3 was about .3 to .4 meters lower than the other mills. The wind was predominately from the NW. If the corona current released from the array on the 12 meter high pole was significant and produced a space charge shielding for the site, then field mill #1 would show a lower value for the electric field. A plume of negative charge from the array would provide a shielding effect down wind in this case. The corona current measuring system gave a low value and did not appear to be working properly at this time.

An estimate of the electric field at the top of the 12 meter pole can be made from the form factor vs. height plot, Fig. 7, since the pole with the array of points on top resembles a field mill tripod in rough form. The field measured over the field mills on tripods 1.8 meter above ground would be multiplied by a factor of at least (3). This would make the field over the array greater than 35 KV/m, a value at which detection of space charge down wind may be expected.[7]

In Fig. 8 the chart records of corona current from a single point and field mill #1 are shown for site C-74. In this case the corona current increases as a linear function of the electric field. S. Chapman has pointed out that this appears to be the case at high wind speeds.[8] The other field mills and corona current monitoring systems were not operating at this time.

At site C-9 measurements were somewhat more difficult due to remoteness and necessary range operational restrictions. Measurements at the ground surface did not show any effect from high corona current generated by the array on the 300 m tower. The simultaneous measurement of the electric field over and the corona current from the array on top of this tower is shown in Fig. 9. Measurement of just the electric field from this location is also shown in Fig. 10. The large swing of the electric field from +400 KV to -400 KV is of particular interest. An op-amp (741) modified to give a non-linear response was used to measure the corona current. The maximum value did not exceed .5 ma. This was considerably less than values reported for the array on this tower during several thunderstorms. The swing of the electric field over the top of the tower went from over +400 KV/m to -400 KV/m per lightning stroke. Since the ground wire from the dissipation array to ground was severed like a blown fuse, one wonders about the current in this wire during electrical storms with near lightning flashes to ground. An order of magnitude determination of $\Delta F/\Delta t$ was not possible, but an estimate of di/dt may be made from what is known about lightning. One flash or strike from cloud to ground may consist of from 1 to 26 strokes occurring over a period of several hundred milliseconds. The

duration of a stroke is around 50 μ sec $\simeq$ 100 μ sec and the interval between strokes 50 m sec. The rise time to maximum current in a stroke is like 1 or 2 μ sec. but a tail of 50-100 μ sec. follows. These time periods may be compared to the period of the characteristic frequency of the tower, i.e. $f = \frac{1}{2}\pi(1/LC)^{\frac{1}{2}}$, when $L = \mu_o/4\pi$ x tower height and $C = 4\pi\varepsilon_o$ x tower height.

$$f = \{2\pi(4\pi \times 10^{-7} \times 300 \times 4\pi \times 10^{-12} \times 400 / 4\pi)^{\frac{1}{2}}\}^{-1}$$

$f \simeq 200$ KH_z where the period, $(t) \simeq 5 \times 10^{-6}$ sec. The time for a pulse to travel the length of the tower on a wire is 400 n/c $\equiv 10^{-6}$ μ sec. So when the electric field swings from +400 KV/m to -400 KV/m, what order of magnitude currents would be expected in the grounding wire over a period of a few μ sec? Actually, ΔF may have reached 10^6 V/m because the recorder was pinned as the chart record shows. The charge on the array, (Q), which must be neutralized per 1 μ sec would give an estimate of the current.

$$Q = \rho A, \quad A = 25 \text{ m}^2$$

$$\rho = E\varepsilon_o = 4 \times 10^5 \times 9 \times 10^{-12} \simeq 39 \times 10^{-7} \text{ c}$$

$$Q \simeq 25_{M2} \times 39 \times 10^{-7}_{c/M2} \simeq 1.0 \times 10^{-4} \text{ c}$$

$$I_{ave} \simeq 10^{-4}_{c}/10^{-6}_{s} \simeq 100 \text{ amp}$$

To sever the grounding cable, considerbly more energy must be made available. A direct cloud to tower lightning strike will be considered. Some means of concentrating I^2R lightning in a 10 $\sim$ 20 cm length of cable is required. Therefore, the back e m f and the energy stored in the LC circuit will be considered. The inductance (L) per unit length of the cable is $\mu_o/4\pi$; $\mathcal{E}$ (per unit length) = $Ldi/dt = 10^{-7} \times 10^5/10^{-6} = 10^4$ volts/ m, $\mathcal{E}$ per cable length = 3×10^6 volts. The

energy in the magnetic field $= \frac{L \times i^2}{2} = \frac{1}{2}\{10^{-7} \times 300 \times (10^5)^2\} =$ 2.00×10^6 joules. The heat required to melt 10 cm of 00 cable is:

$$H = (\text{sp. ht.}) \times 70 \times \Delta t = (\text{ht. of fussion}) \times 70 \text{ g}$$

$$= .1 \times 70 \times 10^3 + 70 \times 43 = 10^4 \text{ calories or } 2360 \text{ joules.}$$

There is sufficient energy in the magnetic field, yet the mechanism to converting it into an I^2R effect over a short length of cable, i.e. about 10 ∿ 20 cm is not evident. The contribution of several factors seems possible. The cable has a natural frequency of 200 k Hz, with the amplitude of oscillation dying to a ½ value in $t = \frac{2L}{R} \ln 2$ or 30 ms. So when $\Delta E = 10^6$ V/M over the tower during a near lightning flash, an estimate of the energy in the oscillating LC circuit may be computed from

$U = \frac{1}{2}(Li^2 + \frac{Q^2}{C})$ when $\frac{Q^2}{C} = 0$: $\frac{Li^2}{2} = \frac{10^{-7} \times 30 \times 10^4}{2} = 1.5 \times 10^{-2}$ joules.

Then consider when this energy is stored in the electrostatic field:

when $U = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2} CV^2$, $V = (\frac{U}{C} \times 2)^{\frac{1}{2}} = (\frac{1.5 \times 10^{-2}}{10^{-8} \times 3})^{\frac{1}{2}} = .5 \times 10^6 =$ 7.0×10^2 V.

This is far short of breakdown potential between the tower and the cable. However, if the dissipation array were hit directly by a lightning strike with several strokes in a 100 ms period of time, the energy stored in this LC oscillator would be roughly 10^8 times greater per return stroke and breakdown, with voltages of 10^7 across (C), i.e. between the cable and the tower would be more likely. At breakdown, an arc may be struck which would generate intense local heating. This arc could be sustained in part by the back e.m.f. generated as the high initial current in the return strokes begins to decrease. There

would be enough energy stored in the electrostatic or electromagnetic field to melt more than 10 cm of (00) cable. During an electrical storm in September 1974, the circuit used to drive a recorder and monitor the corona current from the array on top of the tower at C-9, was destroyed. It was also observed that over 10 cm of new cable (installed August 1974) had disappeared at about 200 M from the ground; the ends were neatly melted off numbs. There was no report of the tower having been hit by lightning during this period. However, it seems that this must have happened in order to explain how the cable was severed.

During fair-weather the potential gradient (F) at the surface of the array ran around 50 KV/m. One would expect it to be greater than $F_o \times h$ = 50 V/M x 300 M = 45,000 V. The array would be at ground potential so one may expect dV/dZ = 45 KV/m low estimate of (F). In the case of electrical storms: $V = 10^4 \times 400 = 3 \times 10^6$ V, but the measured value was only 5×10^5 V/m. The array on the tower top slopes upward about .4 M in 1 M, which would tend to give some field enhancement to top center. The considerably less than expected value of (F) demonstrates shielding due to an increase in space charge and reduction of the potential gradient at the array surface or tower top where the return or leader strokes would originate. Therefore, the array on the tower at C-9 may have generated enough additional space charge to reduce the number of cloud to tower lightning strikes.

At numerable points above and below the point where the new cable was severed, there were scars on the tower structure where flash-over arcs must have occurred. In July 1974 insulation repairs on the old ground cable appeared to be numerous. This would support the theory that breakdown may have been induced by several contributing factors. The significance of peak voltage swings in the LC circuit formed by the 300 m array to ground cable seems credible. The tower structure would contribute to the magnitude of the (LC) for this circuit, lowering its natural frequency, but increasing the capacity for energy storage. A return stroke from cloud to the array would more likely occur when a near lightning flash to ground would induce a ringing oscillation in this circuit. Providing electrical connection between the array and the tower at the top and at intervals for the cable may have given better array performance.

Summary

The analysis and interpretation of measurements made at the Eglin AFB from July 1, 1974 to February 1, 1974 in the study of dissipation array performance have been presented. Representative data has been selected to show the maximum affects as observed in the study. Copies of the recorder charts are enclosed where it was pertinent to the discussion.

At C-74 measurements made with the field mills on the ground did not detect the generation of space charge by the arrays. The comparison of corona current from the single point and the plate of points gave a variable difference. The plate always gave a greater current than the single point, usually at least 3 times greater. The inexplainable variations and changes in polarity of the current from the points lead to questions

about the electrical ground (earth) and the electrical conductivity of the soil. Soil resistivity during dry periods, i.e. just before a rainstorm, was measured by the Wenner method several times near CZR bunker at C-74. The average values ran around 2 - 3 x $10^6 \Omega$ cm which is very high. This may contribute to some electrostatic effects and influence the array performance. The confusing factor at C-74 was the reverse polarity of the current from the points during fair weather, i.e., the points were at a negative potential with respect to ground. It varied with the wind as one would expect. This matter was not explainable with available data.

The measured corona current from the array on the C-9 tower was not greater than 1 ma during electrical storms. However, the space charge in the atmosphere over the tower may have produced a significant shielding effect and reduced lightning strikes from the clouds to the tower. Corona current from the array was not sufficient to neutralize the electric charge in clouds during electrical storms.

The assistance of Mr. Marlin Forstrom, Range Development and Safety Laboratory, Eglin Air Force Base, is gratefully acknowledged. The work of technical assistants, Randy Freeman, Peter Carlson, and Clyde Johnson was very much appreciated.

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Appendix I

An estimate of the electric space charge distribution down wind from an array was made on the basis of reported high corona currents (I)[1]. Order of magnitude values of (F_o) near the ground and in the free atmosphere below clouds (F_h) during storms, and the mobility for small ions[2] (k) are employed. Corona currents up to 150 ma during electric storms have been reported[1] from the array on C-9 over a 10 month period.

The effects on (F_o) for a range of corona current values, i.e., from .1 ma up to 100 ma will be considered. The value of ΔF_o due to the space charge for a distance of 3 km down wind from an array when a 10 m/sec (20 miles/hr) wind was blowing will be determined. Values of the current can be extended by multiples of 2, 5, 10 and etc.; the same applies to values of (F) and the wind speed (v_x). Using typical calues for (F) and (k) the space charge center down wind from the tower may be computed for a case when there are no or few lightning strokes within a distance of 10 km from the tower. At ground level (F_o) will run around 10 to 30 kv/m. In the free atmosphere below the cloud base values of (F_h) from 80kv/m have been reported[3,4]. Typical values of (F) are difficult to assign because of the variations in storm intensity and distance of the site from the storm center. The presence of a relatively small amount of space charge in the atmosphere produces a readily measurable affect at the earths' surface: where $\Delta F = 2\Delta Q/4\pi\varepsilon_o r^2$.

The following picture; portrayed in a sketch, Figure 1 of the situation is roughly indicative of conditions during electrical storm activity within 10 km of a tower with an array. Table 1 summarizes values of ΔF downwind at ground level for increasing values of corona current and a reasonable range of values for (F_h) from .5 to 4. km above ground. A steady wind of 5 m/sec was assumed. In the free atmosphere, velocity of ions in vertical direction (v_z) varies directly with (k) and (F), neither of which are known precisely for the prevailing types of weather to be encountered in this case. After reviewing the literature: 3,4,5 values which seemed reasonable were selected.

The distances an ion would move in the horizontal direction, due to the wind (v_x)., and the vertical direction due to (F_h), are used to determine the approximate position of the space charge center downwind from the tower. The initial value of (F_h) was a guess after considering the literature, sited above, with the increments in (F_h) based on the quadratic relationship between the corona current (I) and (F), $(I) = kF^2$ [6], where the reported range of (I) was used as a rough indication of the dynamic range during different storms reported for this region[5].

The classical time constant of the free atmosphere near the ground is about 15 min., i.e. $\tau = \varepsilon_0/\lambda$ where λ is the polar electrical conductivity and ε_0 is the permittivity of free space. In 10 minutes about half of the ions in the corona current generated downwind space charge would have recombined. There would be some additional losses with precipitation. The polarity of ΔF would

be opposite in polarity to that of (F_h) or (F_o) prevailing for this region at the time. During fair weather (F_o) or (F_h) is negative, i.e. a positive ion would move towards the earth's surface in the free atmosphere.

For the case of (F_h) = 50 KV/m, assuming that ½ of the space charge had recombined: $(\Delta F_o) = 2Q/4\pi\varepsilon_o r^2 \simeq 2Q/10^{-10}r^2 = 2 \times 3/10^{-10}(1.8 \times 10^2)^2 = 15$ KV/m, (ΔF) seems large. So assume that 1/10 of the space charge has recombined: $\Delta F_o \simeq 3$ KV/m, which should be detectable. In the plum of space charge $\lambda_+ >> \lambda_-$ for the case in Figure 1. The mobility (k) of nigative ions moving out of the cloud above will be less than (k) for fair weather annd would reduce the possibility of a higher recombination rate, i.e. when $\lambda_+ \simeq \lambda_-$ in the plume.

On the basis of this preliminary analysis, field mills were placed on the ground to measure (F_o) on a continuous basis with the expectation that ΔF due to the corona current generated space charge could be measured. Two sites were selected on the Eglin AFB, C-9 and C-74, at which measurements would be made up and downwind from an array. This would provide new information on array performance and on more effective use in protection from lightning.

Table 1

Corona Current (I)	Space Charge Released in 10 min. (Q)	Electric Field in Free Atm. (F_h)	Vertical Velocity of Ions (v_z)	Downwind Ave. Height of Space Charge (Q) (h_{ave})	ΔF
0.1 ma	0.06 c	5 KV/m	.5 m/sec	450 m	6.0×10^2 V/m
1.0	0.6	16.0	1.6	780	1.9×10^4
10.0	6.0	50.0	5.0	7800	3.4×10^4
100.0	60.0	160.0	16.0	4600	4.0×10^4

$(k) = 10^{-4}$ m^2/volt sec

$v_x = 10$ m/sec (20 mile/hr. wind)

$v_z = k(F_h)$

$h_Q = v_z 600$ sec

$r = \frac{1}{2}(h_Q) + 300$

$\Delta F = 2Q/4\pi\varepsilon_o r^2 \approx 2Q/10^{-10} r^2$

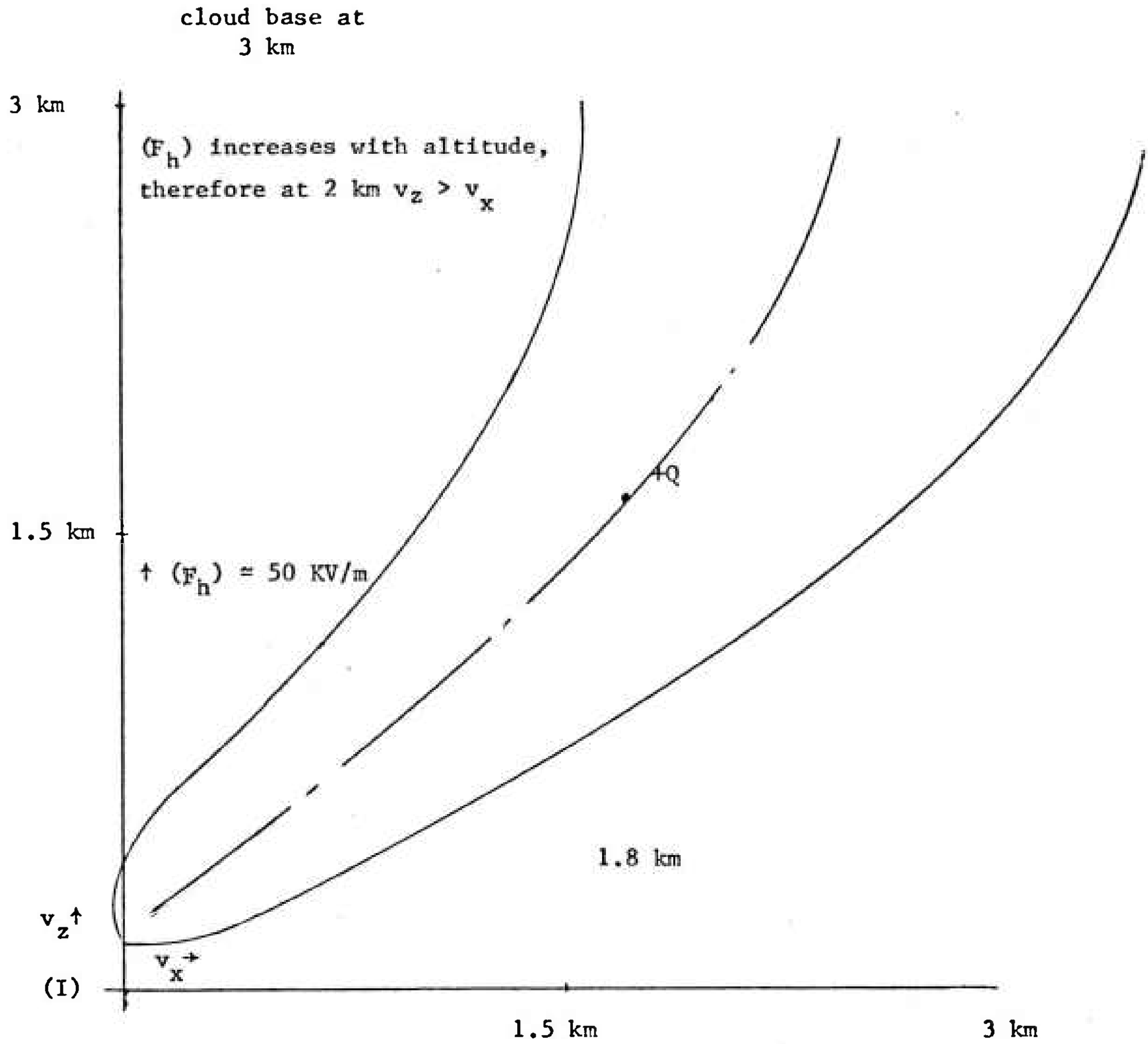


Fig. 1 In this sketch—disregard all currents from the tower array before t = 0. At t = 0; v_x = 5 m/sec, (F_h) ave. = 50 KV/m, v_z = 5 m/sec, the corona current (I) from the array is constant at 10 ma after t = 0. The space charge is carried downwind in a plume as shown above with a center at 1.6 km altitude 1.7 km from the tower after 10 min.

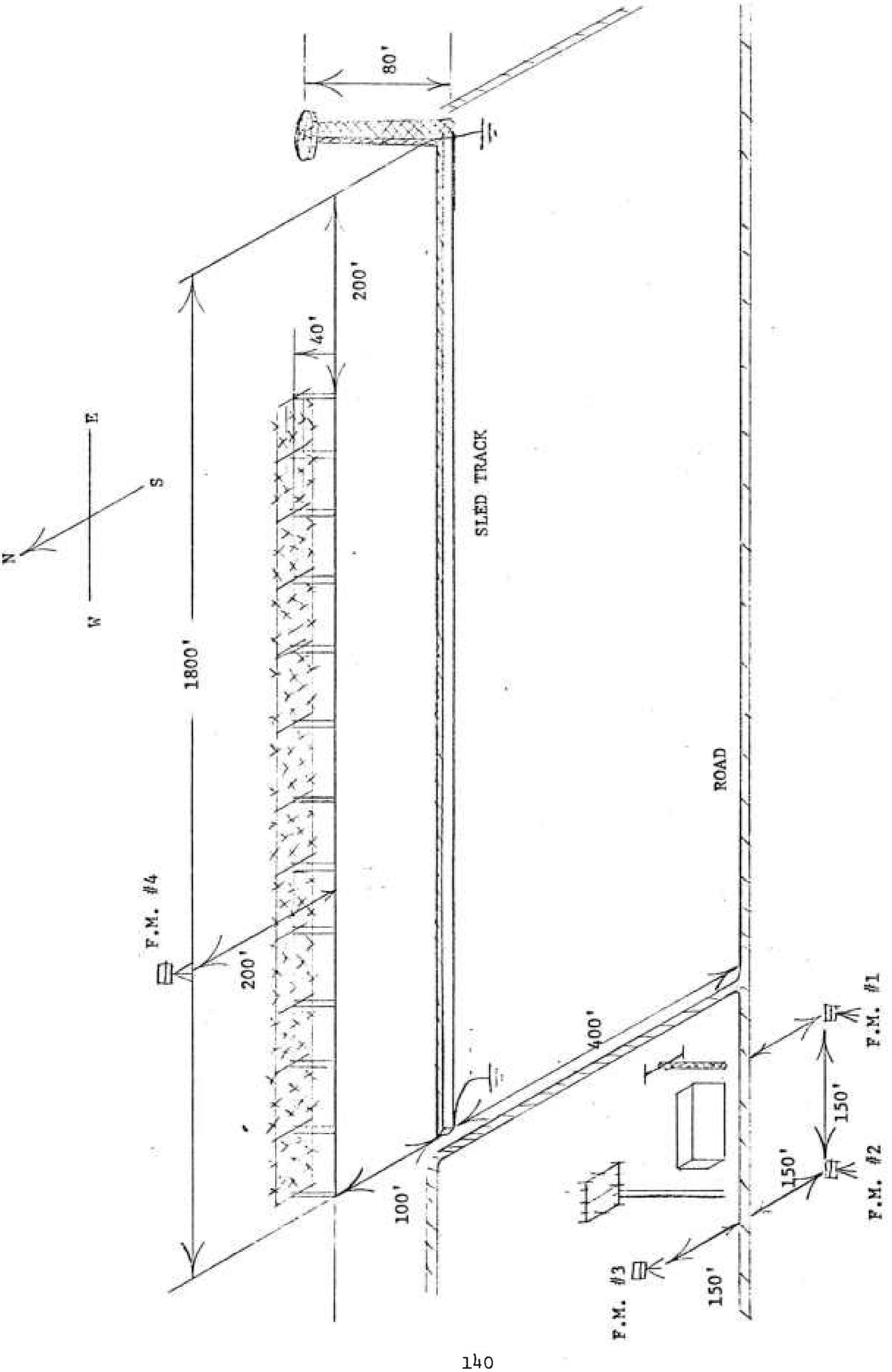

N
S
W
E
80'
200'
40'
1800'
SLED TRACK
ROAD
F.M. #4
200'
400'
100'
F.M. #1
150'
F.M. #2
150'
F.M. #3
150'

fig. 2

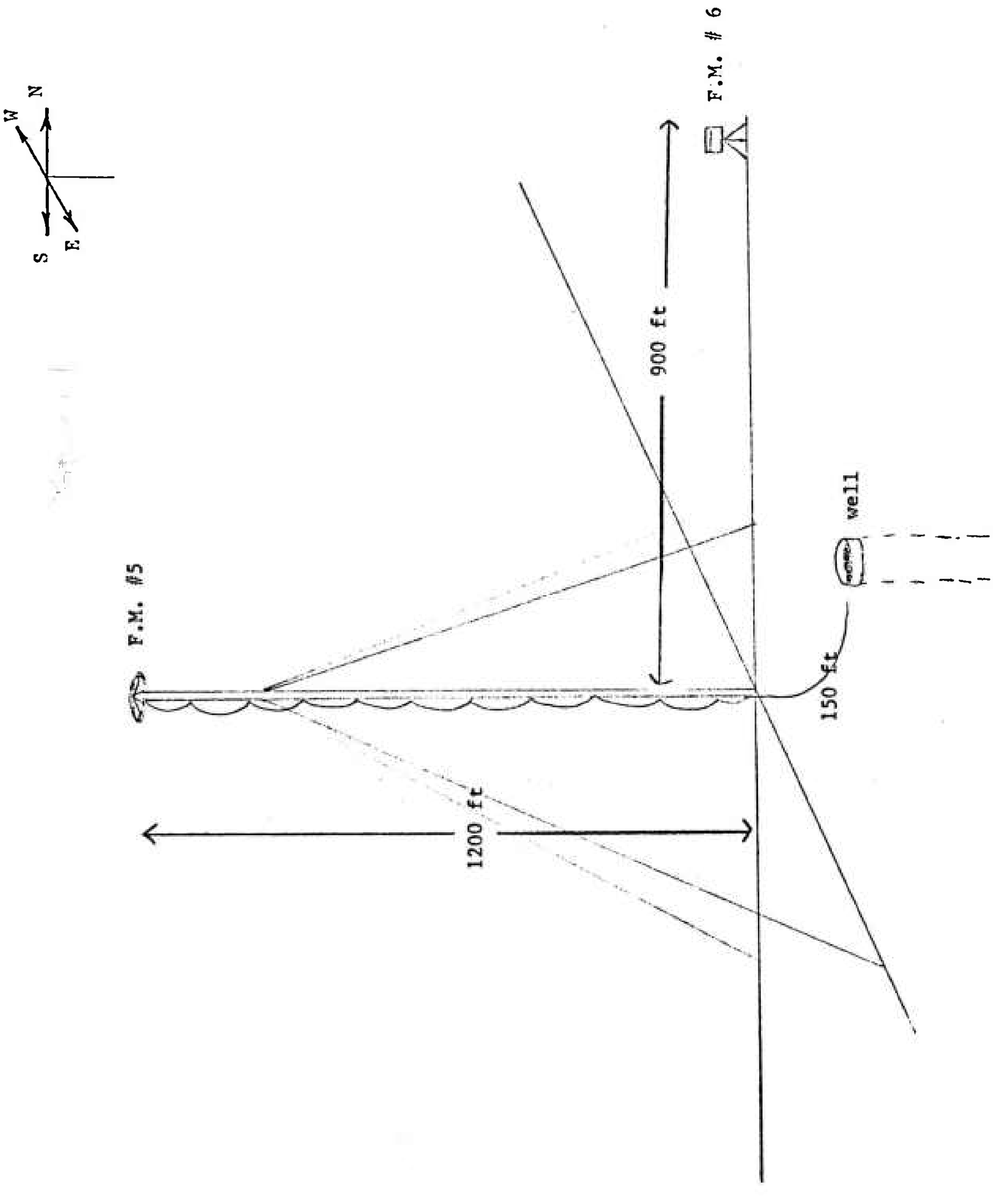


fig. 3

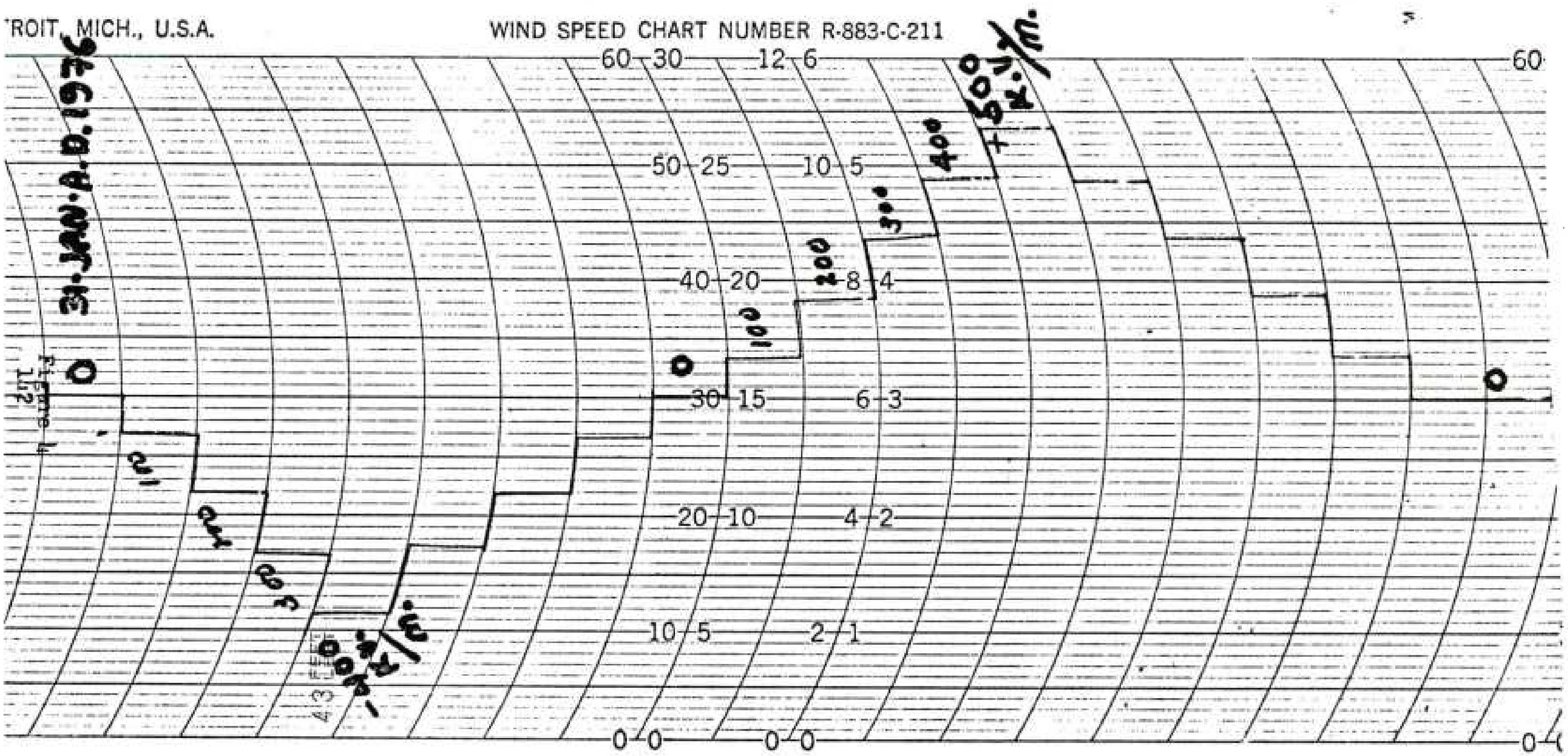

TROIT, MICH., U.S.A.
WIND SPEED CHART NUMBER R-883-C-211
31.JAN.A.D.1976
60 30 12 6
50 25 10 5
40 20 8 4
30 15 6 3
20 10 4 2
10 5 2 1
0 0 0 0
60
+500 K.V./m.
400
300
200
100
-400 K.V./m.

Figure 4

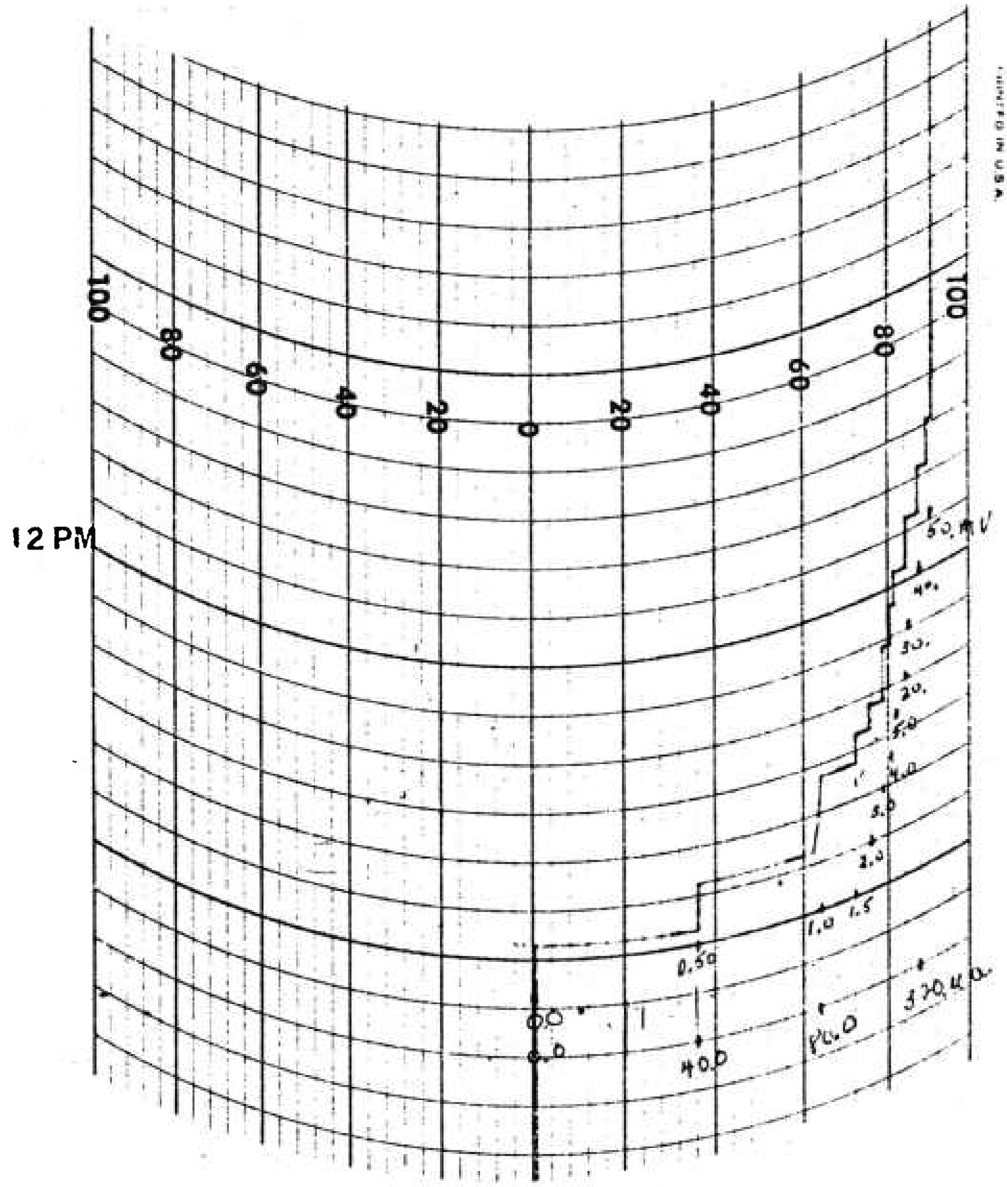
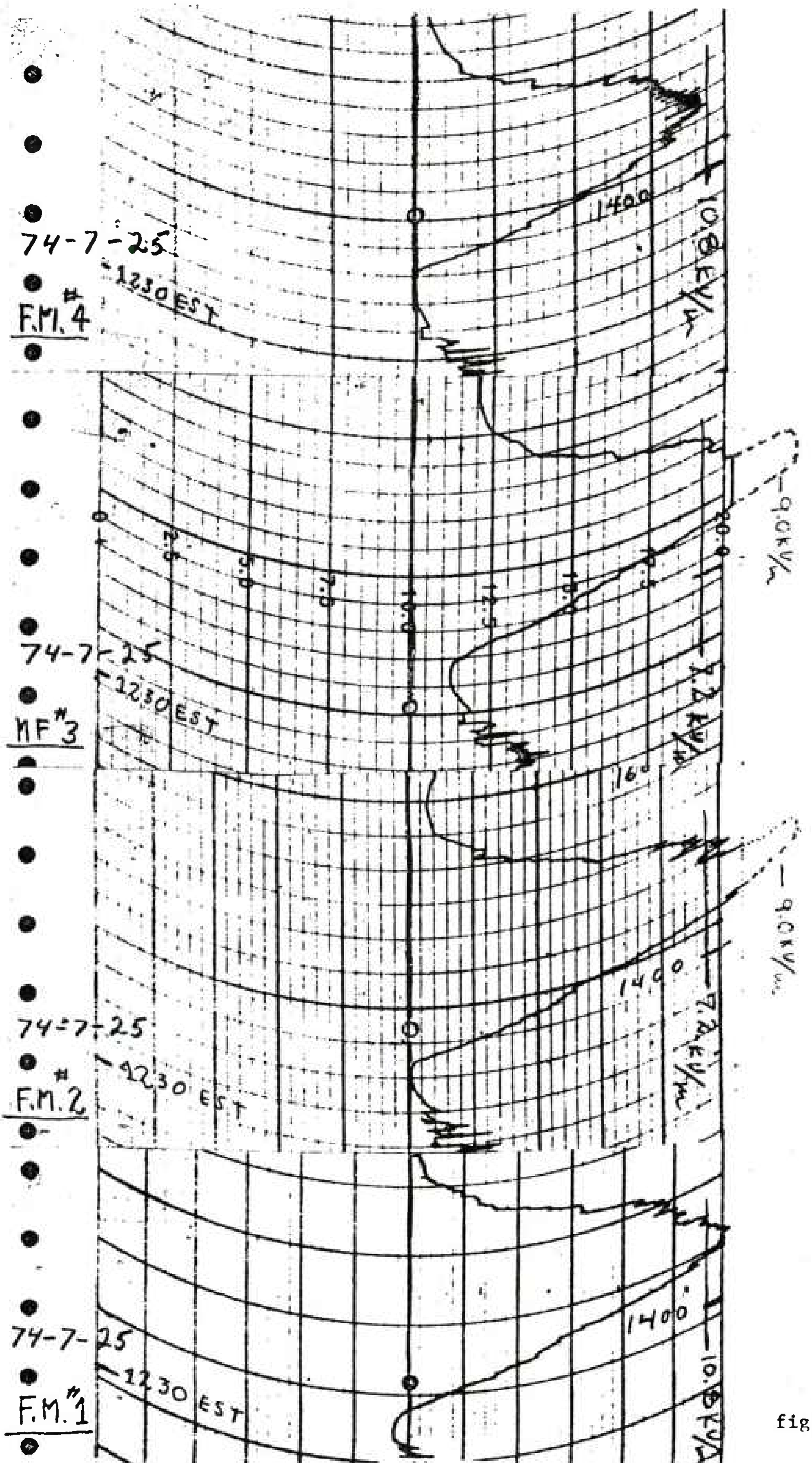

100
80
60
40
20
0
20
40
60
80
100
12 PM
40.
30.
20.
5.0
4.0
3.0
2.0
1.0
1.5
0.50
40.0

fig. 5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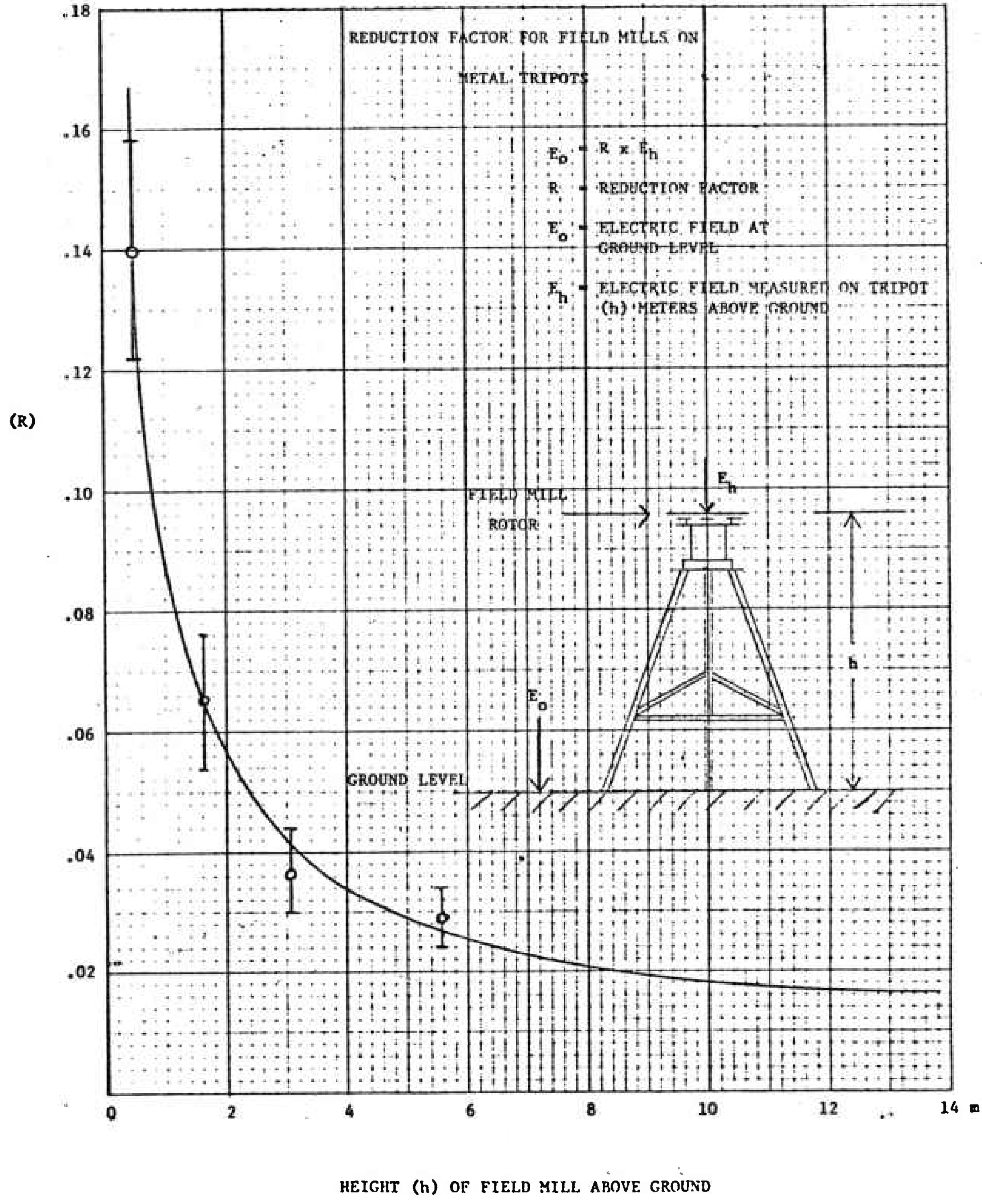
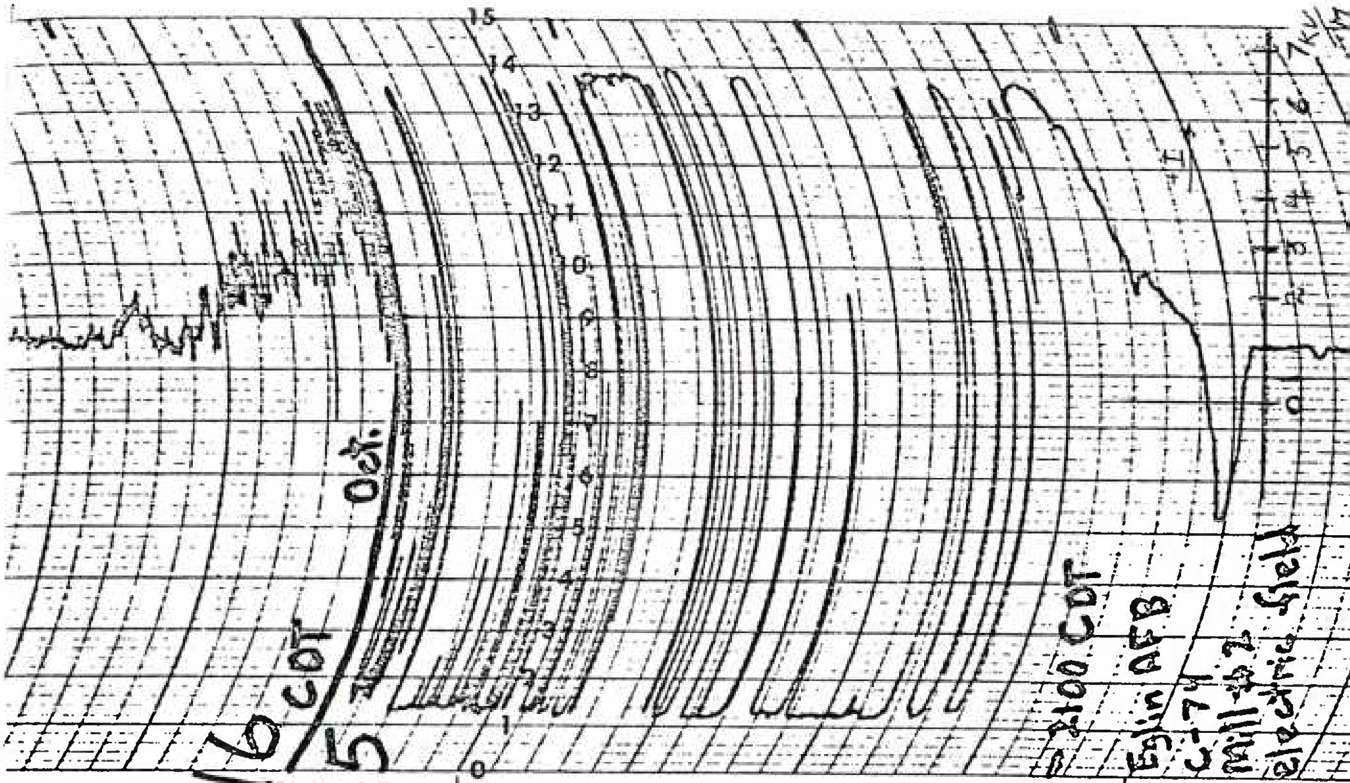
1230 EST
F.M.#4
1400
10.8 KV/m
74-7-25
1230 EST
MF#3
9.0 KV/m
7.2 KV/m
74-7-25
1230 EST
F.M.#2
1400
9.0 KV/m
7.2 KV/m
74-7-25
1230 EST
F.M.#1
1400
10.8 KV/m

fig. 6



REDUCTION FACTOR FOR FIELD MILLS ON METAL TRIPOTS
Eo = R x Eh
R = REDUCTION FACTOR
Eo = ELECTRIC FIELD AT GROUND LEVEL
Eh = ELECTRIC FIELD MEASURED ON TRIPOT (h) METERS ABOVE GROUND
FIELD MILL ROTOR
Eh
Eo
h
GROUND LEVEL
(R)
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
2
4
6
8
10
12
14 m
HEIGHT (h) OF FIELD MILL ABOVE GROUND

fig.7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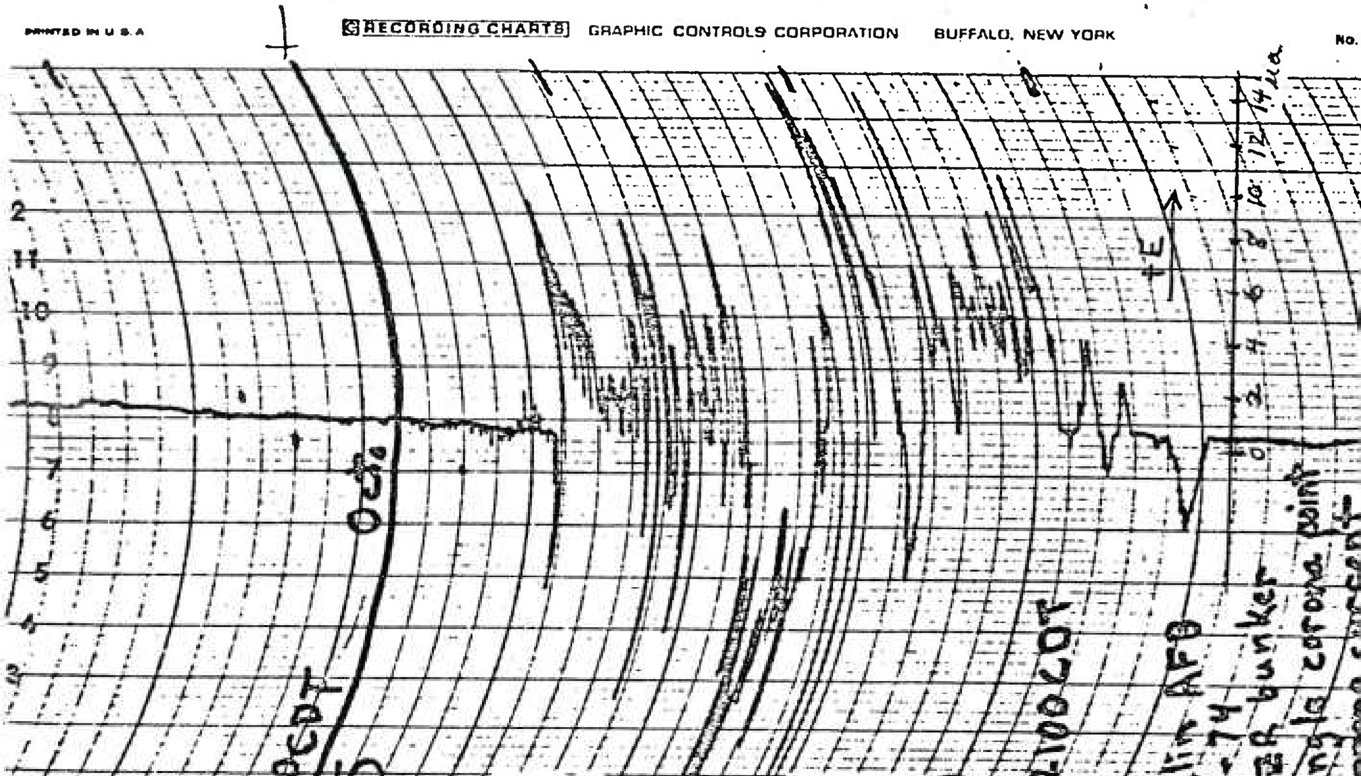
15 Oct.
2100 CDT
Eglin AFB
C-74
mill #2
electric field
+E


PRINTED IN U.S.A
RECORDING CHARTS
GRAPHIC CONTROLS CORPORATION
BUFFALO, NEW YORK
No.
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15 Oct.
2100 CDT
Eglin AFB
C-74
bunker
single corona point
+E

fig. 8

(160)

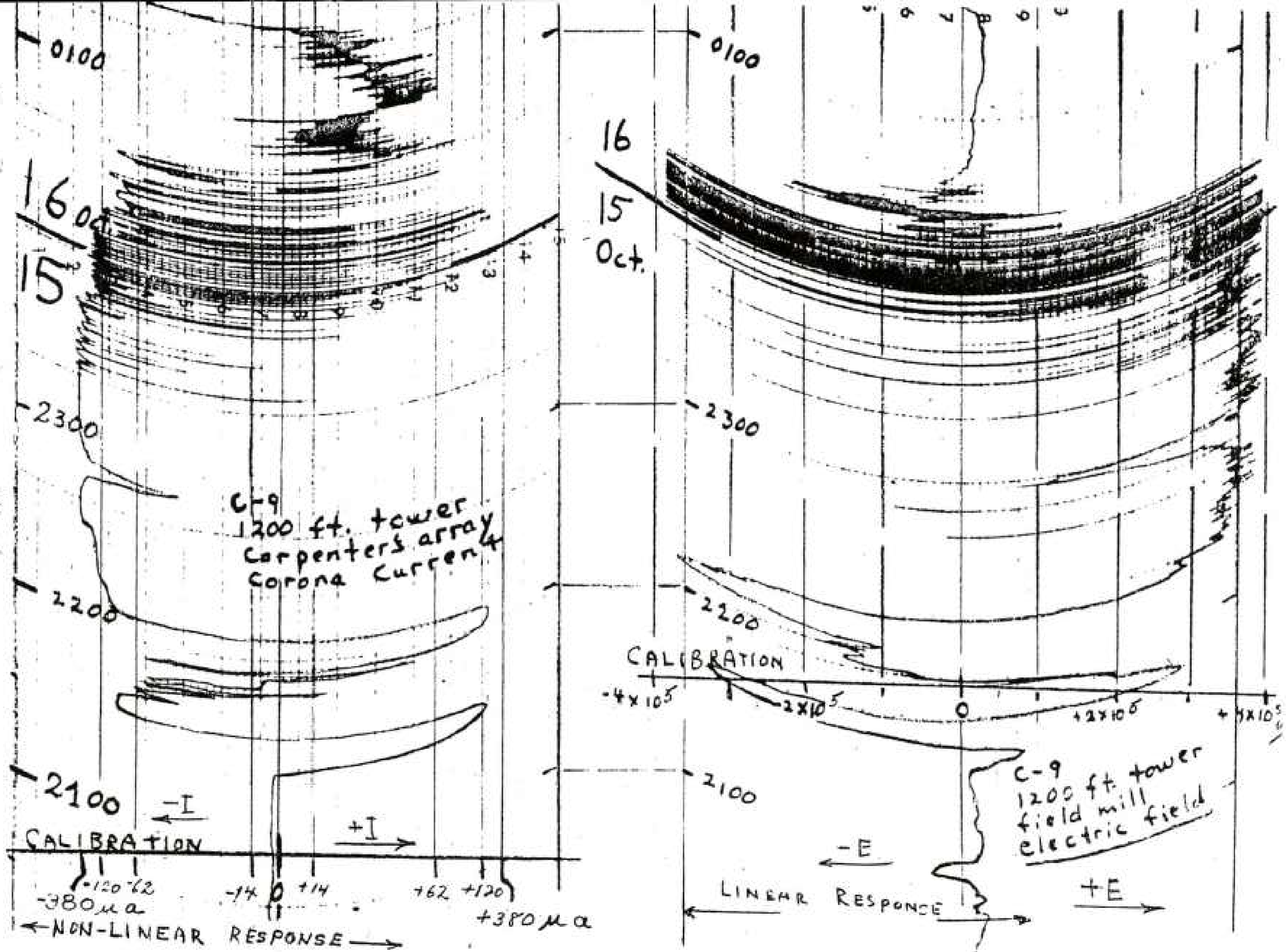
0100
16 00
15
2300
2200
2100
C-9
1200 ft. tower
Carpenters array
Corona Current
-I
+I
CALIBRATION
-120 -62
-380 μa
-14 0 +14
+62 +120
+380 μa
← NON-LINEAR RESPONSE →
16
15
Oct.
CALIBRATION
-4 x 10^5
-2 x 10^5
0
+2 x 10^5
+4 x 10^5
C-9
1200 ft. tower
field mill
electric field
-E
+E
LINEAR RESPONCE

fig. 9

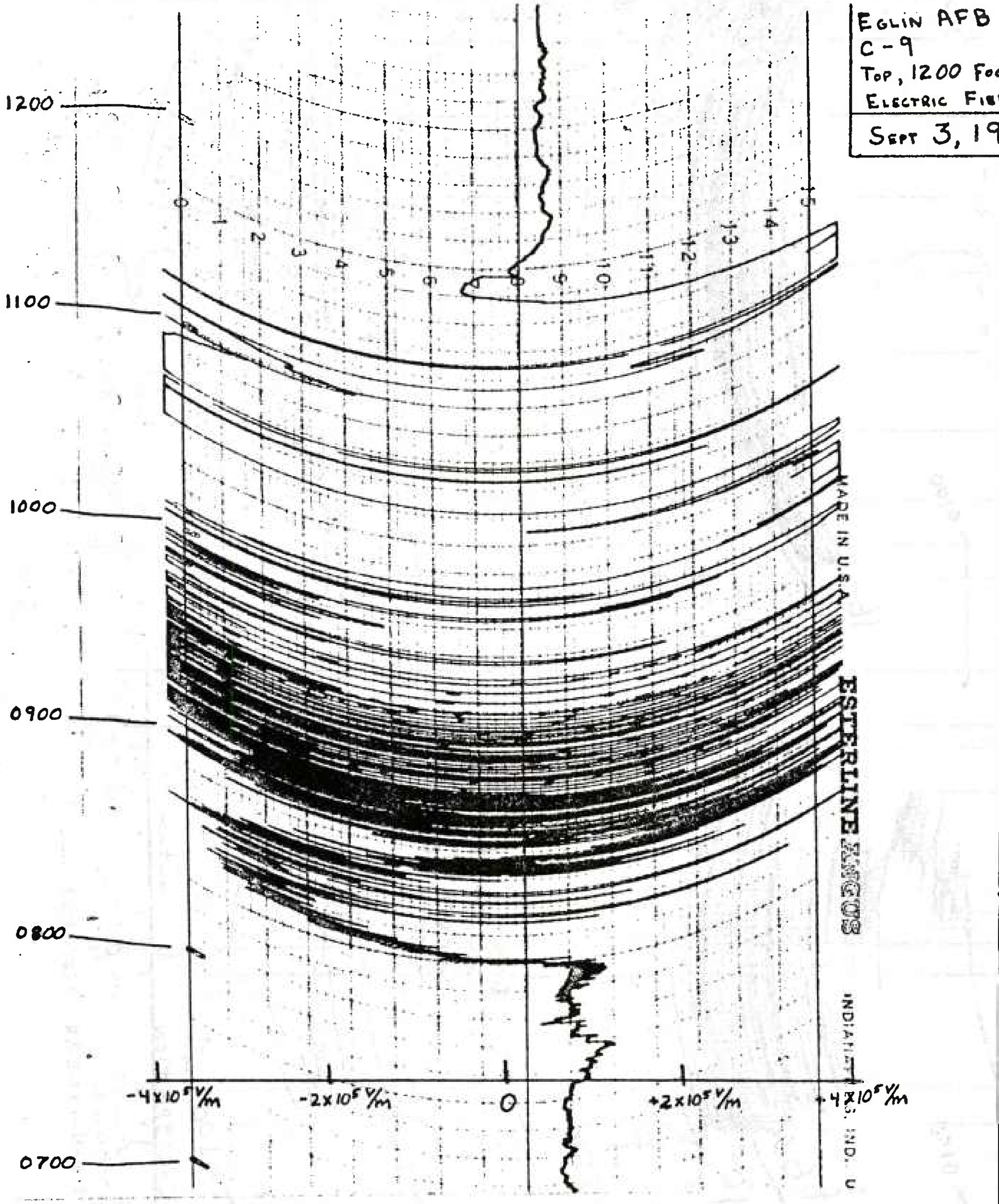
EGLIN AFB
C-9
TOP, 1200 FO
ELECTRIC FIE
SEPT 3, 19
1200
1100
1000
0900
0800
0700
-4x10^5 V/m
-2x10^5 V/m
0
+2x10^5 V/m
+4x10^5 V/m
MADE IN U.S.A.
ESTERLINE ANGUS
INDIANAPOLIS, IND. U

fig. 10

AN INVESTIGATION OF THE LIGHTNING ELIMINATION AND STRIKE REDUCTION PROPERTIES OF DISSIPATION ARRAYS

by

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November 6, 1975

This work was performed for ONR under contract N00014-73-C-0348

TABLE OF CONTENTS

TABLE OF CONTENTS (cont)

LIST OF FIGURES

LIST OF FIGURES (cont)

LIST OF FIGURES (cont) Page

AN INVESTIGATION OF THE LIGHTNING ELIMINATION AND STRIKE REDUCTION PROPERTIES OF DISSIPATION ARRAYS

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ABSTRACT

The dissipation of thunderclouds to the point where lightning is inhibited has been a topic of conversation for over two hundred years. Such ideas have been put forward but have usually been denounced by scientists. This study is primarily to investigate recent claims of success in eliminating lightning by corona principles from multiple points. These claims are made by a California manufacturer who has supposedly protected a number of sites of U. S. Government establishments from lightning. The sites under investigation were primarily the NASA/GSFC tracking site at Cape Kennedy, Florida and the USAF Eglin Air Force Base, Florida facility. These sites housed protected areas and a protected 1200 foot tower. Further investigations were carried out at NASA/Rosman, N. C. Inquiries were made about similar and independent investigations at NASA/KSC and at a non-government Central Florida location and contacts were made with certain radio stations and power companies housing the elimination arrays. Corona tests were carried out on the arrays under investigation, as well as independently on single point and multiple point arrays.

Every possible area was investigated and the report discusses in detail the historical, theoretical, physical, statistical and experimental aspects of these arrays, as well as reviewing the reports claiming success. All this analysis points conclusively to the fact that the arrays do not eliminate lightning. The photographic and experimental evidence also indicates that the arrays do not protect any area from lightning and no evidence has been found suggesting a reduction in the strike rate to such regions. It is suggested that these arrays do no more in protecting an area or a tower than do conventional lightning rods.

1.0 HISTORY OF THE DISSIPATION CONCEPT

It is a common misconception that lightning rods discharge clouds and thus prevent lightning. The rod only serves as a means to route the lightning harmlessly to ground by diverting the lightning when it approaches the striking distance at about 10 to 100 yards away. The lightning leader is "unaware" of any feature on the ground until it has come to within this striking distance. In the two hundred years since Benjamin Franklin investigated lightning many manufacturers have tried to influence the public in the dissipation principle of lightning protection or elimination. This technique most certainly does not work and the lightning physicists' thoughts on this subject are discussed in masterly fashion by Golde[1] in the following statement:

> It is a manifestation of human weakness that a prejudice once acquired tends to be retained even in the face of overwhelming factual evidence contradicting the basis on which it was founded. In the realm of science a prejudice may be termed a misconception. Such a misconception which has persisted for over two hundred years and which is still widespread is the belief that a lightning conductor has the ability, or indeed the purpose, of dissipating silently the electric charge in a thundercloud thus preventing the "protected" building being struck.

The long history of the interest in the dissipation possibility started when Benjamin Franklin first put forth his idea on the lightning rod furnishing two alternative explanations of its action. He suggested that the rod would conduct the stroke to ground thus eliminating any damage, or that the rod might prevent lightning, this idea being derived from laboratory experiments of point discharge. In his publication in Poor Richard's Almanac in 1753 he definitely leaned toward the attraction principle. One of the first buildings equipped with a lightning rod was the bell tower of St. Mark's in Venice. It had been completely destroyed by lightning three times and severely damaged nine times in a period of about 400 years. In 1766 a lightning rod was installed and no further lightning damage has occurred since.

In 1930 a U.S. patent was granted to J. M. Cage[2] of Los Angeles, California for a dissipation system claiming to protect areas and structures against lightning. In its main application of shielding petroleum storage tanks, wires armed with points were suspended from steel towers completely enclosing the area to be protected and aiming at the prevention of lightning discharges by dissipation.

Another application of the dissipation idea is found in the radioactive lightning rods, which supposedly utilize the excess ionization to help protect against lightning. Golde in his book on Lightning Protection[3] examined these claims. A response was made by the medical profession, by Roberts et. al. in 1966 [4] who were worried about the use of the typical radioactive sources for therapeutic purposes, which exceeded the intensity

of the radioactive rods by a factor of 5×10^6. When directed toward the roof of the hospital room, these sources would induce a very serious lightning hazard if the claims made for the much weaker radioactive rods were justified. But fortunately there is no evidence that therapeutic rooms in hospitals are struck more frequently than other structures in the same region! Cassie in 1969(5) further examined the effect of a radio therapeutic source theoretically and found that even for such an intense emitter the striking distance would only be reduced by 6 to 10 cm, which leaves the effect of the much weaker radioactive rod completely negligible.

A number of well known scientists have discussed the dissipation possibilities. The charging current in a thunderstorm has been measured in various ways to be of the order of one ampere. To prevent lightning by dissipating this charging current, according to Chalmers,(6) 50,000 points would be needed within the area of intense field below the cloud. This area is about 1 km^2 requiring the points to be located about 4.5 cm apart which is clearly impractical. These numbers are based on a maximum current of 20μA given off by a single point, and on excessive values of updraft, assuming erroneously that the corona discharge could reach the charge center of the cloud. Looking at the problem in terms of charge transferred, Chalmers states that based on an average value of 30 coulombs brought to ground during a lightning flash, it would take a single point about 2 1/2 weeks to neutralize this charge. In an average storm the lightning flashes occur at intervals of minutes, so again the order of 50,000 points would be needed.

Golde (1) looks at this problem in a similar fashion. Considering average electric fields of 200 V/cm under a thundercloud, an average charge of 30 coulombs being dissipated by a lightning flash, and a flash rate of two per minute, it follows that 6,000 conductors each 50 feet high and spaced over 1/2 square mile would be required to prevent one lightning flash.

Extremely high point-discharge currents have been measured at the top of the tower on Mount San Salvatore in Switzerland. On occasion currents of up to 4 mA were recorded on this tower of effective height in excess of 2500 ft lasting for the order of one half hour depending on the speed of the thundercloud. But in the words of Berger (7) who monitored this data, a single strong lightning stroke can transport more charge than the point-discharge current of a tall tower during an entire summer.

Evidence of the point-discharge can be seen in the form of St. Elmo's Fire, in particular in high mountains where thunderclouds frequently develop only slightly above the peaks creating intense electric fields. While this phenomenon is indicative of a highly charged atmosphere, the currents actually flowing might not be that extreme. According to Chapman(8) 10μA of corona current can be seen as a glow under the right circumstances, and 100μA are easily visible.

It has been argued that adding more points to the lightning conductors would increase greatly the amount of corona current given off. Chalmers(6) quotes about eight experimenters who have investigated single point versus multiple

point corona currents. In general it is found that in the laboratory multiple points will give off more corona current than a single point, however under the actual conditions in the field, the results are the other way around and more corona current is obtained from a single point. This discrepancy is due to the relative distances between cloud and ground and the points, which cannot be properly simulated in the laboratory between plates and test points.

As has been found in some recent advertisement literature the supposed power of the dissipation principle has been even further exploited for the elimination of hail and the prevention of the growth and maturity of typhoons. It is also suggested that objects with dissipation points being dragged into the ocean from aircrafts or released from submarines will dissipate the surface charge on the oceans over considerable distances. Considering the results from the above mentioned investigations of many scientists, these claims seem hardly justifiable.

2.0 THE PHYSICAL PROCESS RELATED TO CLOUD DISSIPATION

Figure 1 shows a typical thunderstorm cell in the early stages of development. At that time the cloud has reached a height of only 28,000 feet and the general flow of air under the cloud is upward. In order to investigate whether the corona discharge released at the ground will pass into the main charge region of the cloud, we can assume a typical vertical motion due to updraft of an uncharged particle to be no more than 8 feet/second.

25 min →

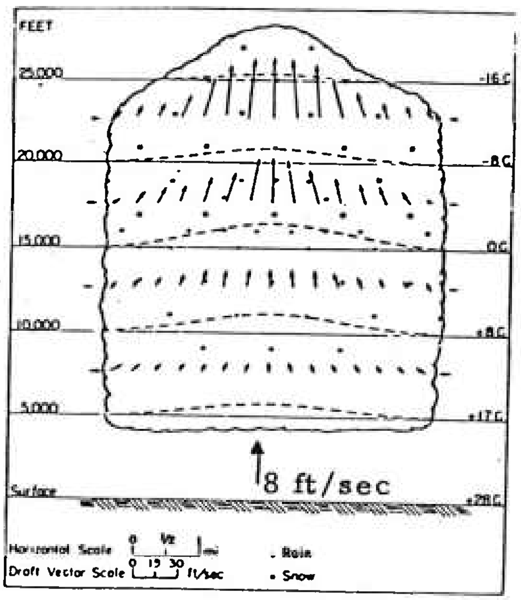


Fig. 1 A thunderstorm cell in the early stages of development. (From U.S. Dept of Commerce Weather Bureau Report, June 1949).

This uncharged particle will take approximately 25 minutes to attain an altitude of 12,000 feet, should the cloud remain stationary during this time. The ions are, however, charged and will also proceed upward under

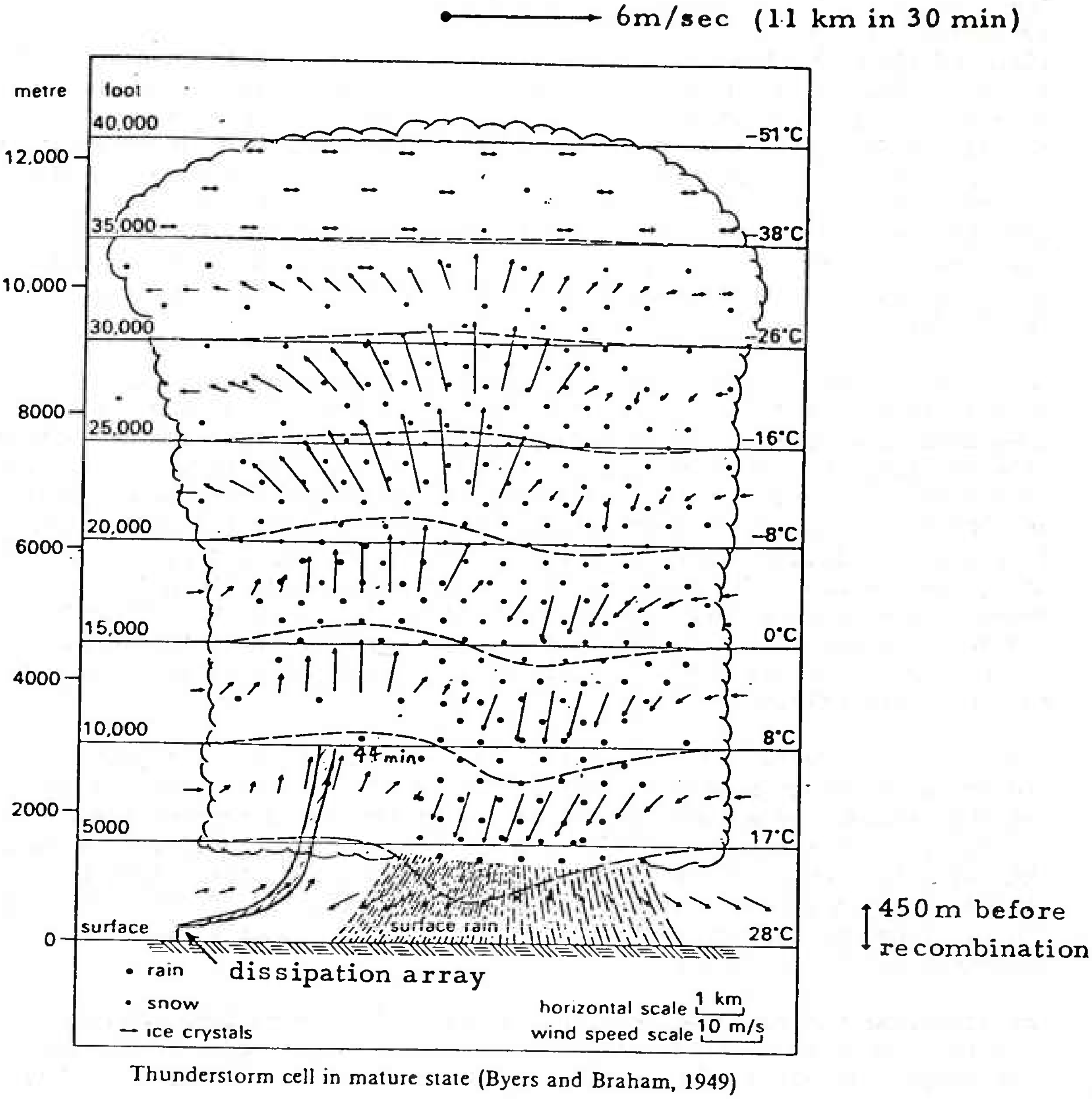
the influence of the ambient electric field. Assuming the mobility of small ions at 1.5×10^{-4} m/sec per V/m and a pre-thundercloud electric field of 2000 V/m, the small ion moves upward under the influence of the electric field at 0.3 m/sec or 1 ft/sec. Let us, however, consider aerosol attachment which limits the lifetime of fast ions to the order of 50 seconds or less in air full of aerosol, and up to 200 seconds in country air. In country air the ions will move under the influence of the electric field for only 200 x 0.3 or 60 meters vertically, after which time they are under the influence of the vertical and horizontal wind alone. Clearly this small distance of 60 meters is negligible when considering updrafts and hence, we can assume that these ions take approximately 25 minutes to reach 12,000 feet.

When the thundercloud becomes more mature the area over which updraft occurs is reduced and considerable downdraft occurs. The typical thundercloud then looks like that shown in Figure 2. If we assume that corona ions are released from the region of maximum updraft, 'A' in the figure, then these ions would take approximately 45 minutes to reach the main charge center at 4000 meters considering updraft alone. Ion mobility for 200 seconds in a field of 10,000 V/m would lower this time by only 1 minute. Furthermore, the average horizontal motion of a typical thundercloud is 6 m/sec, hence in a 44 minute period the cloud will have moved 16 km. Clearly, the corona point will have virtually no influence on the main charge center of the cloud, because the updraft is much too low and the cloud's horizontal motion is significant.

The horizontal surface winds under a thunderstorm can be extremely severe and can often reach speeds in excess of 25 m/sec. In the next chapter the theoretical investigations of the corona process discusses the motion of ions in wind speeds up to 15 m/sec and likens the situation to a factory chimney. In such a situation the smoke indicates the effect that horizontal wind can blow the ions well downstream and that the updraft is comparatively small. Added to this updraft will be the even much smaller vertical component due to ion mobility.

The classical theory on the currents released by corona from grounded objects under the electric field of overhead thunderclouds, indicates that these currents form part of the atmospheric electric circuit of the thundercloud which should be considered a generator of current and not of voltage. Consequently, modification of the distribution of this current by the erection of artificial passive discharging points or arrays will not have any effect on cloud electrification or the incidence of natural lightning.

The external dissipating current from a thundercloud is the order of 1A, but the actual charging current is several times this value, a large portion of this being dissipated internally mainly by conduction. The values quoted are for a whole storm which normally consists of several cells in various stages of development. For thundercloud dissipation to occur, no less than an additional 1A of current must pass to the cloud. If this current can reach the main charge center of the cloud from the ground which, in view of the foregoing wind investigations seems unlikely, then the dissipating arrays must be capable of dissipating an extra 1A which is in contradiction to the classical theory just examined.



Thunderstorm cell in mature state (Byers and Braham, 1949)

Figure 2. Thunderstorm Cell in Mature Stage Showing Updraft Region and Possible Ion Flow

It has already been pointed out in the previous chapter that corona current from single points in the field has been measured by many scientists who have reported it to be higher than multiple point corona current. The amplitude of the corona current is a function of the magnitude of the electric field, the wind speed, the radius of curvature and the height of the point. Golde(3) indicates that for a conductor several tens of meters high standing in open country, the current amounts to a few microamps. Chalmers(6) also summarizes results indicating similar values in high fields. In fact, it can be assumed from many previous findings that under very high

fields and with strong winds, the corona current from a sharp point atop a 100 foot tower exceeds that from a multipoint array, and the currents are much less than 100 A.

Natural sources, such as trees are known to have given corona currents in excess of 1 A per tree with a tree separation of 3.4 m, Bent [9] and Schonland [10]. This figure is approximately equivalent to 1mA per 100 m square, implying that a 35 m square area of trees will emit more corona current than single or multiple points atop a 30 m tower in a clearing of similar area. These statements are derived from results quoted in the past by many scientists, but are also backed up by data taken during this investigation and reported in later chapters.

It has been suggested in some circles that a protective shield of ions can be produced from dissipating arrays in order to protect the area beneath from the thundercloud charges. Such a shield would, however, be much more dangerous to the ground than the cloud above it and the suggestions cannot be viewed seriously.

The foregoing summary strongly implies that lightning incidence in an area beneath the cloud is unlikely to be affected by corona point emitters at the ground.

3.0 TYPES, OBJECTIVES AND PHYSICAL CLAIMS OF ARRAYS INVESTIGATED

The lightning elimination and dissipation arrays investigated under this study were manufactured by Lightning Elimination Associates of Downey, California and purchased by the U. S. Government. Hence, all the tests reported herein unless otherwise mentioned, were carried out on U. S. Government owned arrays. The following information has been gathered from official reports from the manufacturer submitted to the U. S. Government and from nationally distributed publications, all of which are listed in the references.

The arrays in use at these sites are of various designs but the basic idea is to have many sharp points for corona dissipation over the area of the array. There are in general two types of material. One is termed dissipating wire which looks very similar to barbed wire and typically has four points spaced every 7 cm along the wire; the four points are separated by approximately 90° around the wire and are of length 2 cm. The other material is formed on a rigid metallic panel with protruding sharp points and is similar to what one may expect in a fakir's bed of nails. The material is conducting and typically has 4 cm high sharp points separated by 6 cm. It has been claimed that the type of conducting material is important but, to our way of thinking, as long as the material is conducting and the point maintains its sharpness, its type is irrelevant. The electric field lines around the point are unaffected by the material type if it is at ground potential and also, since the avalanche process causing the ion formation occurs in the high field around but outside the point, its material type cannot effect the corona density.

The dissipating wire is the material used to form the umbrella array, the truncated cone and the barrier types of arrays, whereas the rigid conducting material forms a disc or panel array. Figure 3 shows an umbrella array installed on a 100 foot collimation tower at NASA/GSFC's satellite tracking station on Merritt Island, Florida. The array is approximately 20 feet in diameter and is comprised of the dissipating wire wrapped spirally around the "umbrella" framework. A close-up of the array is shown in Figure 4. Approximately 1000 feet of the dissipating wire is used in such an array.

A barrier array is shown in Figure 5. Such an array can house any length of the dissipating wire and the one illustrated is installed at the NASA/GSFC Rosman satellite tracking facility. The height of the array is 40 ft and it has seventeen strands of wire each separated by over 1 ft running for a length of 170 ft, giving a total wire length approaching 3000 ft.

The truncated cone array is attached to a tower and is made up of a number of dissipating wires formed around the tower in guy rope fashion. This type of array, however, puts a considerable portion of the dissipating wire in a region of reduced electric field thereby lowering the amount of corona current and increasing the field required for initial corona breakdown. Such an array is shown in Figure 6 underneath an umbrella array located at the NASA/GSFC Rosman facility. At times the dissipating wire is passed around the roof perimeter of a building, as is shown in Figure 7. This array is also at the NASA/GSFC Rosman facility.

The panel type of array is shown in Figures 8 and 9. Figure 8 shows a small panel atop a wooden pole at site C74 Eglin Air Force Base, Florida and Figure 9 shows a close-up of a panel on top of a 1200 ft tower at site C9 Eglin Air Force Base. The sharp points are easily visible on this panel which was one of three atop the tower; each panel measuring 4' x 6'.

An article in the Journal of Electrical Construction and Maintenance(11) states the purpose of these arrays as follows:

> Rather than attempt to minimize lightning-caused damage and outages by shunting the lightning discharge across a spark gap or arrestor, this method is designed to <u>prevent</u> lightning strikes and the accompanying secondary effects. Basically, a dissipation array is set up to slowly bleed off the electrostatic charges contained in a thunderstorm, thus preventing the buildup of a potential gradient sufficient to result in a strike.

The article continues:

> The system installed at Eglin Air Force Base protects a UHF transmitting antenna mounted atop a 1200 ft tower situated on an 800 ft hill, the highest land point in Florida. Prior to the installation, lightning strikes at this site averaged over 100 per year. In the 18 months since installation, there have been no strikes.

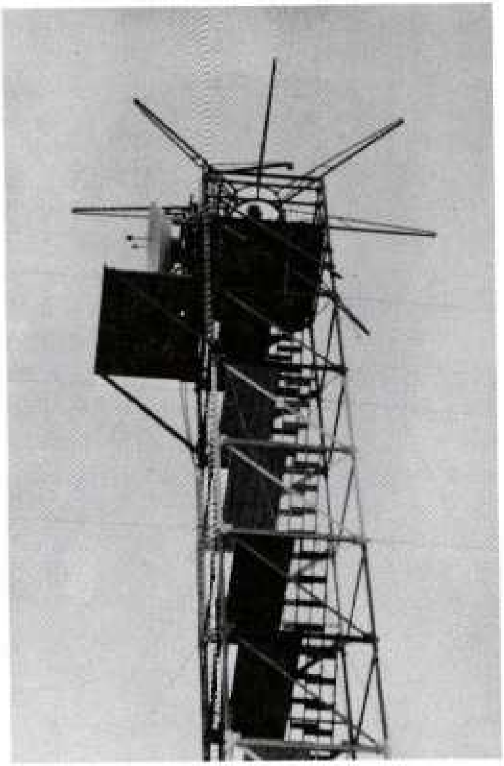


Figure 3. Umbrella array at MILA

Figure 4. Close up of umbrella array at MILA

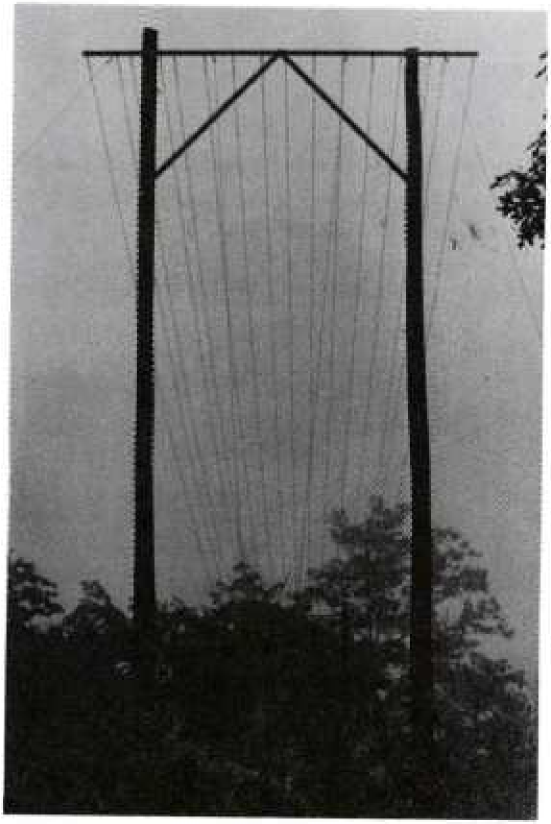


Figure 5.
Barrier array at
Rosman, N.C.

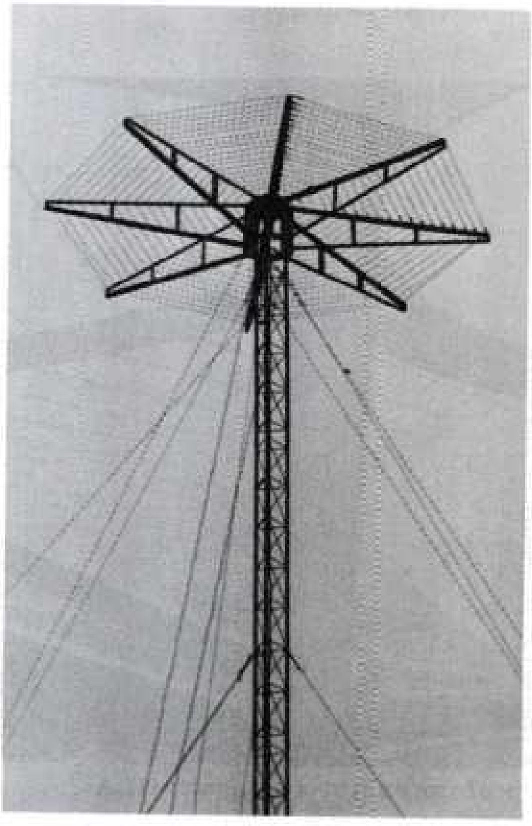
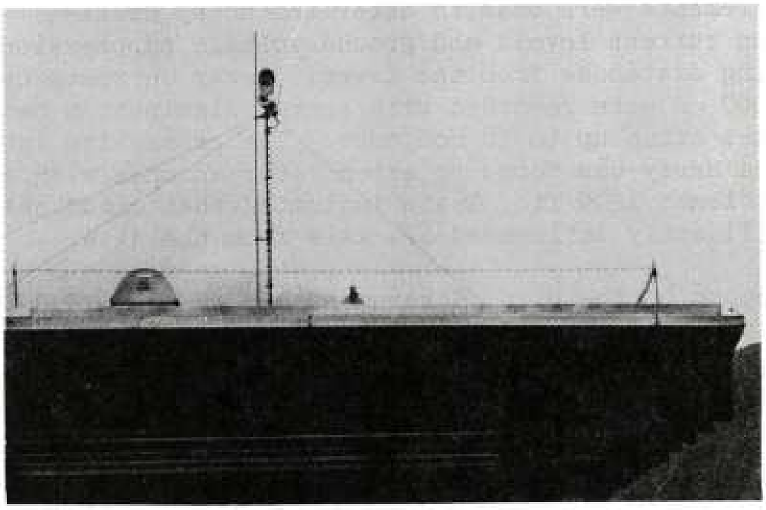


Figure 6.
Guy rope dissipation
wire added to an array
at Rosman, N.C.

Figure 7.
Perimeter array at Rosman, N.C.



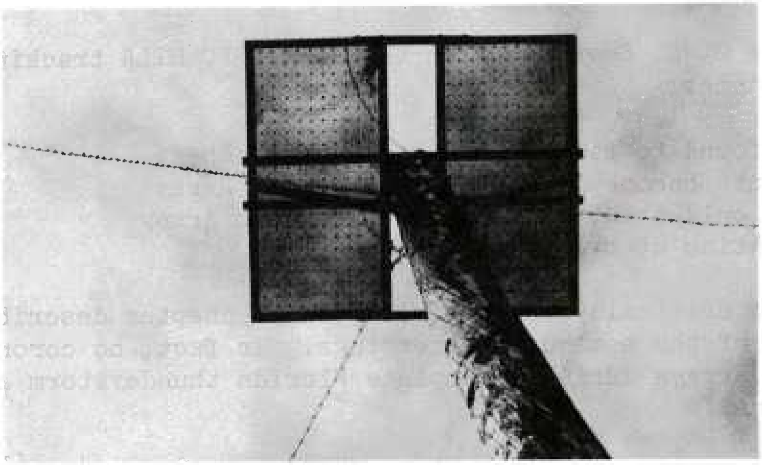
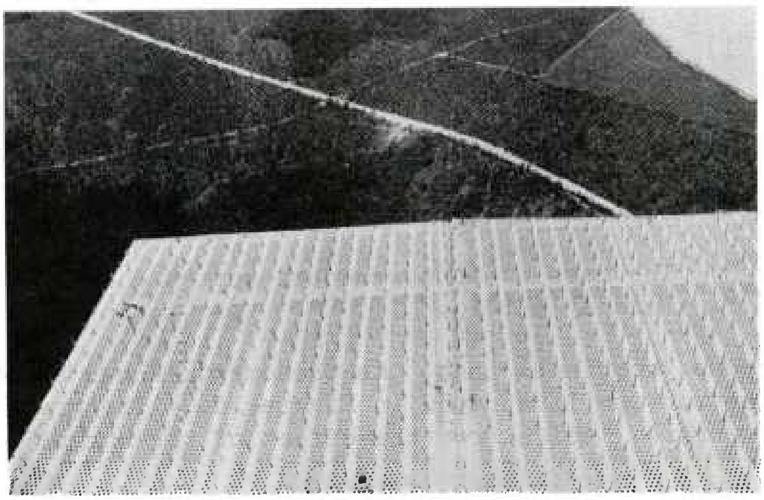


Figure 8.
Panel array at site C74 Eglin A.F.B., Florida

Figure 9.
Panel array atop 1200 foot tower at site C9 Eglin A.F.B., Florida



> Measurements were made to determine array dissipation current levels and ground voltage suppression at varying distances from the tower. Array currents up to 150,000 μA were recorded with energy dissipation between strokes often up to 18 coulombs. The protective influence of the array was found to extend over an area with a radius of at least 1200 ft. Tests indicated that cloud cells were significantly influenced 1/4 mile from the site.

A final report to the U. S. Government[12] on this 1200 ft tower array system states that the dissipation array:

> "1) Actually prevents the lightning stroke.
>
> 2) Dissipates the same energy levels as in a stroke, but slowly over a period of time."

This first statement is strongly disputed in the analysis described in the later chapters of this report, and the second one is meaningless without a time period being quoted.

Another report to the U. S. Government on the NASA/GSFC MILA tracking facility arrays performance states:

> The current is found to rise as the storm approaches, and the transients become larger. The Umbrella Array current rose to only about 25 mA while the Conic Array went into saturation at over 150 mA.

These claims are also critically reviewed in a later chapter describing our independent analysis of the same data recordings. In fact, no corona data taken by us on these arrays during a complete Florida thunderstorm season even came close to 1mA.

The principle of the dissipating system is described in reference [13] submitted to the U. S. Government where the following three statements suggest a reason for the "success" of the arrays in preventing lightning:

> "1) The cloud charge is reduced to some degree, in proportion to the flow of current.
>
> 2) The potential gradient between the cloud and the protected area is reduced by the flow of ions through the intervening air space.
>
> 3) The mass of ions produced act as a form of faraday shield."

The report continues that "the phenomenon known as point discharge and its application is illustrated in Figure 10." The graph displays some very basic errors. Aside from the effect of the normal meteorological elements,

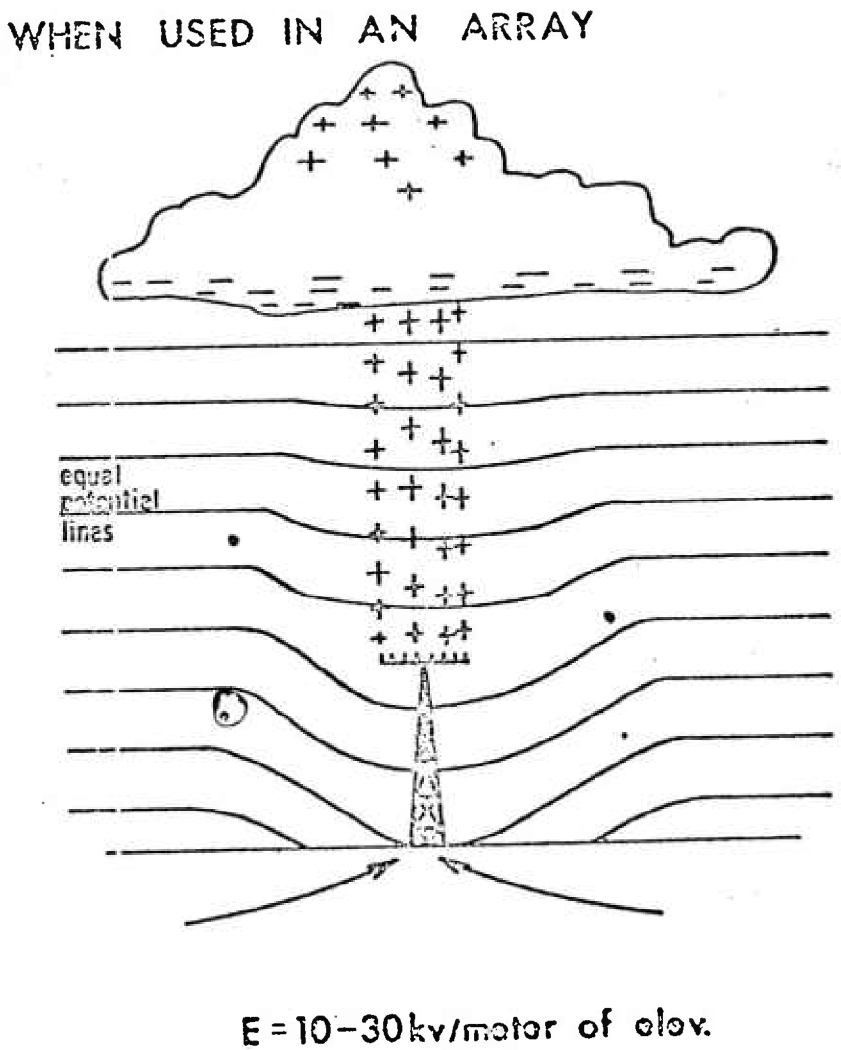


Figure 10. A surprising explanation of cloud dissipation by an array manufacturer

the equipotential lines cannot possibly follow these patterns. By definition the lines cannot cross the grounded structure, but must pass above it and need not necessarily reach a parallel situation beneath the cloud if a region of reduced field is to be shown. The figure, therefore, leads one to believe that we must study very carefully all other physical processes claimed by these manufacturers on the performance of these arrays.

The arrays are not devised just to protect the structure on which they stand, but in most cases the area surrounding them as well. The NASA/Rosman facility is quoted by the manufacturer of the arrays to be protected from all lightning strikes over most of its 180 acres. A proposal was also made by them to install arrays to prevent lightning strikes to any region inside a U. S. Government airport of 412 acres.

It is quoted in reference (14) that an umbrella array at height of 25 feet and 19 feet in diameter can dissipate over 25 mA of current under a potential gradient of 30 kV/m. Such a field would only rarely exist in a parallel field situation. One must assume, therefore, that the 30 kV/m quoted is the field at the tower top. Assuming an exposure factor of 5 for such a situation would correspond to a parallel field of 6 kV/m . Then the quoted current of 25 mA is a factor of almost 10^3 higher than that obtained during this investigation from similar arrays at greater heights under such severe thunderstorm fields.

4.0 STATISTICS OF LIGHTNING STRIKES TO GROUND

A normal negative lightning leader advances towards the ground in discrete steps until it reaches a distance of a few tens of meters above the ground. When the leader is at that height the field at the ground is very high and counter streamers are initiated from various points on the surface. One of these streamers will join up with the downward coming leader to form a path for the large return stroke. It is therefore at that particular distance that the point of strike is determined. This striking distance is defined as the distance between the tip of the lightning leader and the point to be struck at the instant of time when the counter streamer meets the downward leader.

An excellent photograph of the striking distance phenomena just described is shown in Figure 11 where lightning is striking a 500 foot tower at NASA/KSC. This photograph was supplied by NASA/JSC, Houston. At the time of the strike a dissipation array was on top of this tower, but according to the manufacturer the galvanizing process had not been performed properly and the array was not working; it was replaced shortly afterwards. Once more, however, we would like to reiterate that we believe the metallic finish of a grounded conductor should not influence the formation of ions above it in the avalanche process.

For a negative polarity stroke the striking distance varies from about 30 m at 20 kA to 150 m at 150kA. The striking distance for the rare positive polarity strokes is about 50% larger than that for the negative polarity strokes. Hence, the striking distance increases with the severity of the

discharge and for an average 25 kA strike it is about 40 m. More important, however, these results and associated theory show that the progression of the leader remains quite unaffected by any feature on, or below ground, until the tip of the leader has reached a height of only a few tens or, at most, two hundred meters above ground. These results therefore provide quantitative evidence against the belief in lightning attraction areas and raise serious question as to how dissipation arrays can exercise any local influence at all.

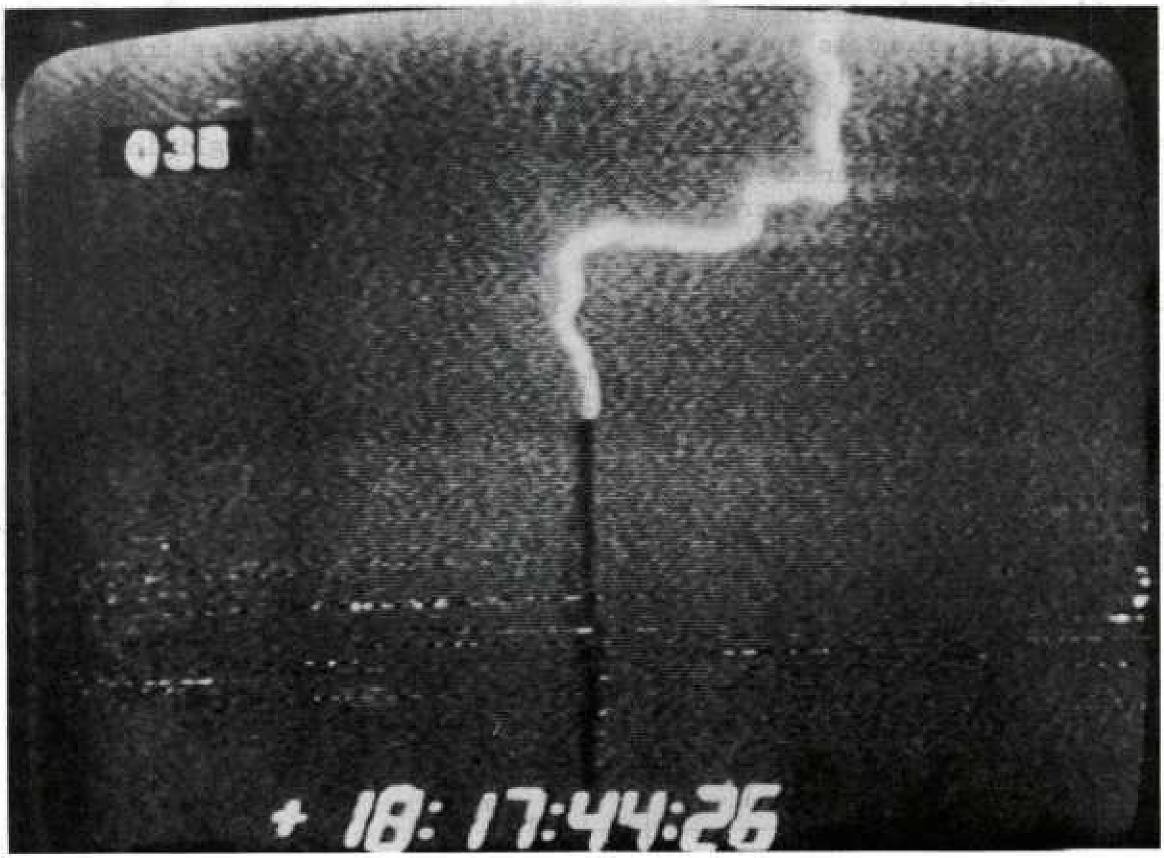


Figure 11.

Lightning striking a 500 foot meteorological tower at NASA's Kennedy Space Center, Florida, and hitting the dissipation array

Cianos and Pierce[15] give a useful relationship for determining the frequency of strikes under a thunderstorm. They conclude that the number of thunderstorm days per month, T_m, and the flash incidence per km^2 per month, σ_m, are related by the equation:

$$\sigma_m^2 = aT_m + a^2 T_m^4$$

where a equals 3×10^{-2}. The ground flash incidence per km^2 per month is quoted as p_m, where p is the proportion of flashes that go to ground. As an example, p = 0.18 in Orlando and 0.30 in North Dakota.

Considering the frequency of strikes to tall structures electrically connected to ground, Pierce and Price(16) have provided more useful data. They indicate that the attractive radius, r_a, and its associated attractive area $A_a = \pi r_a^2$ are primarily functions of the structure height h. The attractive radius is defined as the average radius at which a downward leader from the cloud is just able to induce an upward streamer from the structure that will unite with the downward leader and thus divert the flash to the structure. The triggering factor represents the inclination of flashes to be initiated at the tip of the structure; it is negligible for $h \leqq 100$ m, but as h increases, triggered flashes become increasingly common and for $h \geqq 250$ m the triggered variety of discharge is by far the more important.

Cianos and Pierce (15) indicate that it is difficult to calculate r_a but give a complicated expression for r_a as a function of h. Their expression is based both on mathematical representations emerging from theoretical analysis, and on a weighted empirical fit. Table 1 shows their results. Note however that above 150 m the attractive radius does not change with a further height increase. This is because calculations indicate that for $h \geqq$ the field distribution between the tip of the structure and the downcoming leader is not much influenced by the presence of the ground.

Table 1

Relation Between Structure Height (h) and Attractive Radius (r_a)

h (m)	r_a (m)
25	~150
50	~250
100	~350
150	~400
> 150	~400

Pierce has discussed the instances relating to triggered lightning, and assumes that it may occur when the ambient electric field lies between 3 and 30 kV/m and the voltage discontinuity between the tip of the conductor causing the triggering and the unperturbed atmosphere is 0.3 to 6 MV. The longer these values are maintained and the larger the values, the more likely the possibility of triggering a flash.

Pierce and Price [16] have summarized the best presently available data on the incidence of triggered lightning as a function of height in Table 2. The data base is so scanty that substantial future modifications could occur. Also shown in Table 2 are the information derived from two expressions by Pierce and some theoretical results due to Horvath[17]. None of the theoretical expressions agree well with the experimental data. Horvath's work much overestimates the incidence at lower values of h, and gives underestimates for high h. Expression (1) fits well for h ≙ 150 m but overestimates for large h.

As an example let us consider the 1200 foot or 365 m tower at Eglin Air Force Base then "protected" by a dissipation array. Table 1 gives the attractive radius as 400 m and Table 2 indicates an average value of 10.5 for the ratio of triggered to natural lightning. The incidence of flashes to ground at Eglin Air Force Base is approximately 7.5 km^2. Thus, the annual incidence of natural lightning to the tower should be:

$$7.5 \times \pi \times (400)^2 \times 10^{-6} = 3.77$$

Triggered lightning should contribute a further incidence of some

$$10.5 \times 3.77 = 39.6$$

The total number of strikes to the tower will therefore be on the order of 43 per year, of which the majority are upward initiated.

Table 2

Proportion of Triggered to Natural Lightning

Structure Height (m)	Actual Data	Expression (1)	Expression (2)	Horvath Theory
50	~0	~0	~0	0.1
100	~0	~0	~0	0.2
150	0.3	~0	0.5	0.4
200	1	0.1	2.8	0.7
300	4	1.3	16	1.4
400	10	6	38	3.0

Expression (2) underestimates throughout, but the agreement is becoming better for h~400 m.

5.0 DISSIPATION ARRAY AND CORONA CURRENT INVESTIGATIONS BELOW 100 FEET

5.1 Site Description

The measurement of corona current from an umbrella type dissipation array and from an assortment of single and multiple points took place at the NASA/GSFC MILA tracking facility at Kennedy Space Center, Florida. The NASA staff under the direction of Mr. J. Dowling provided considerable assistance and equipment for the duration of the project. This site was chosen for the investigation because a variety of dissipation arrays of the types discussed earlier were already installed at the facility. Other advantages were its location in an active thunderstorm zone and the fact that comprehensive analysis of results from these arrays had already been received by NASA[18] that claimed some scientifically surprising results.

An aerial photograph of the site is shown in Figure 12. The facility housed a selection of dissipation arrays which were installed during 1974 to provide a lightning prevention system for the complete facility even though there was no evidence that lightning had ever struck it. The dissipation arrays included a 24 sq. ft. panel array located between two 30 foot parabolic dish antennas, a perimeter array around the roof line of the main building, a truncated conic array on a 100 ft collimation tower and a large umbrella array over 20 feet in diameter which was located on the 100 foot collimation tower some 1/2 mile north of the main facility. This distant collimation tower is shown in the upper left hand section of Fig. 13 and most of our investigations were conducted there.

The area is free from man made charge generation, and the vegetation is primarily cabbage palms and palmetto which may easily give rise to natural corona because of their sharp pointed leaves.[9]

A closer view of the collimation tower complete with umbrella array is shown in Figure 13_a, a close up of the array in Figure 4. The building at the base of the tower housed an 8 channel Brush Recorder (Fig. 13_b). Also visible in Figures 13 $_a$ and $_c$ are 3 tripods which were used for corona current and field mill investigations. These tripods were each 20 feet tall and were separated by a distance large enough that they would not normally electrostatically interfere with one another. Field mills were located atop the 5 ft and 20 ft tripods, and the other two tripods were used for corona current investigations.

5.2 Instrumentation

Field mills were erected at 4 heights: 100 feet (Fig 14), 20 feet and 5 feet (Fig 13_c) and at ground level. Corona measurements were carried out at 100 feet from the dissipation array and at 20 feet from two different sources. Wind speed and direction were also monitored halfway up the tower at 50 feet (Fig 13a).

The field mills were installed to investigate the space charge existing during thundery conditions between the heights 0-5, 5-20, 20-100 feet. This data is useful in determining the amount of natural corona discharge emitted from nearby natural sources. The mills were all mounted in an upward direction

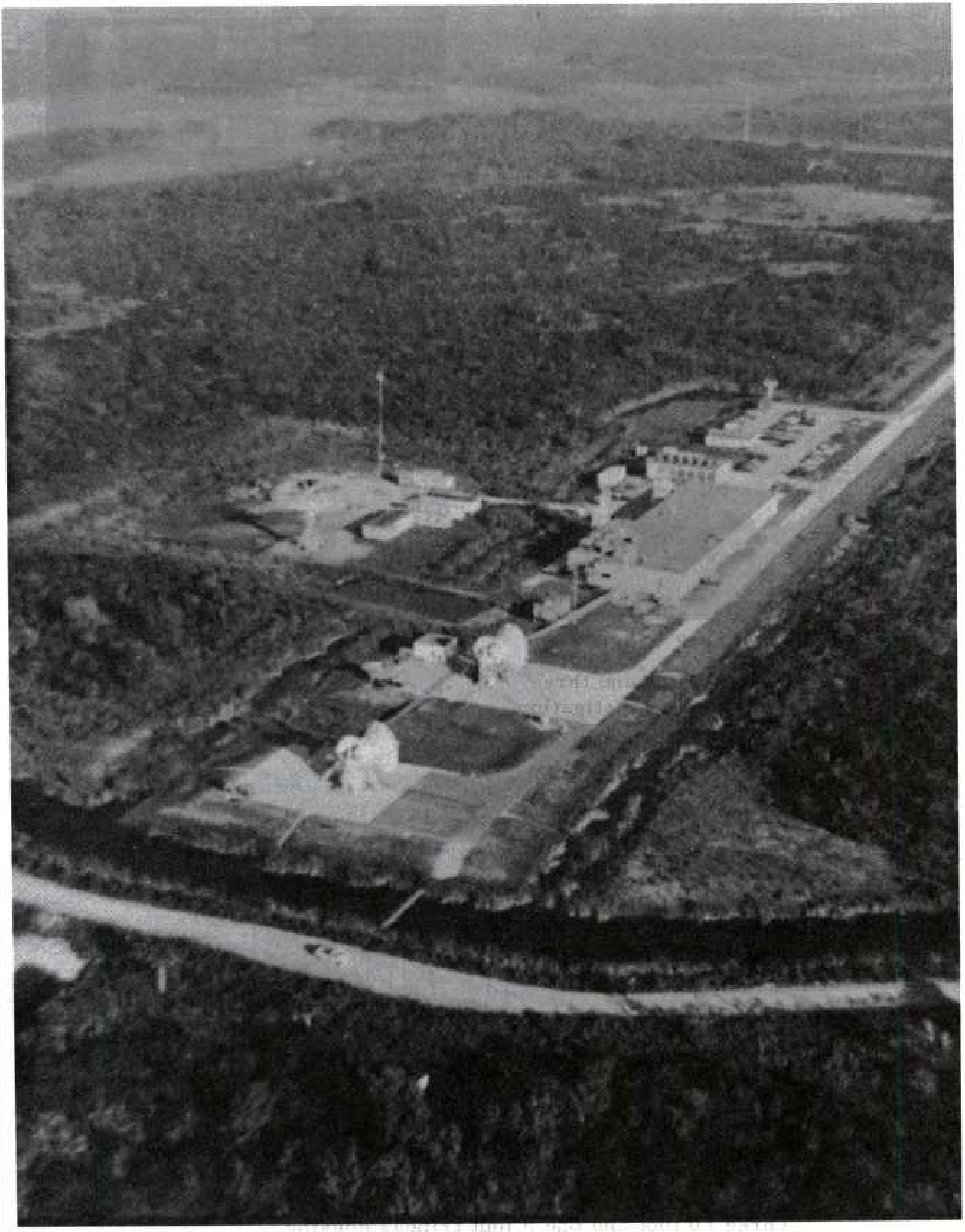


Figure 12. Aerial view of the NASA/MILA tracking site

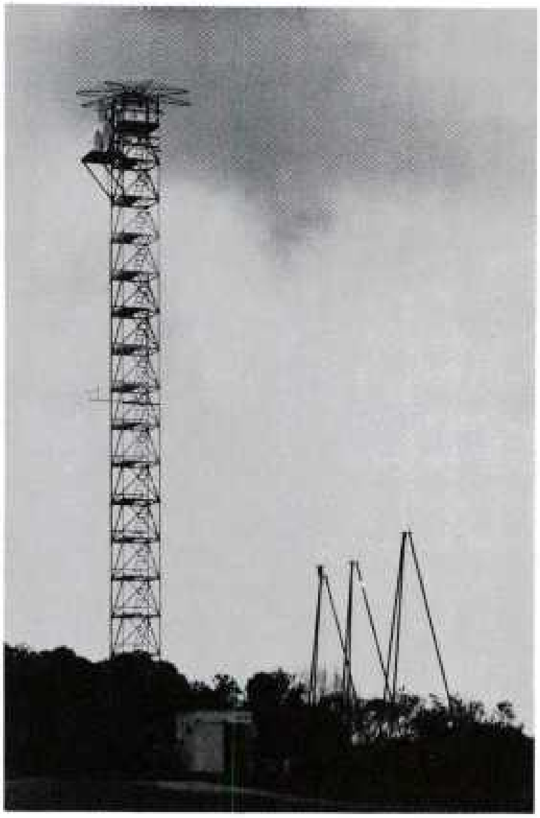


Figure 13 a.

100 foot collimation tower and three 20 ft tripods used in the investigation

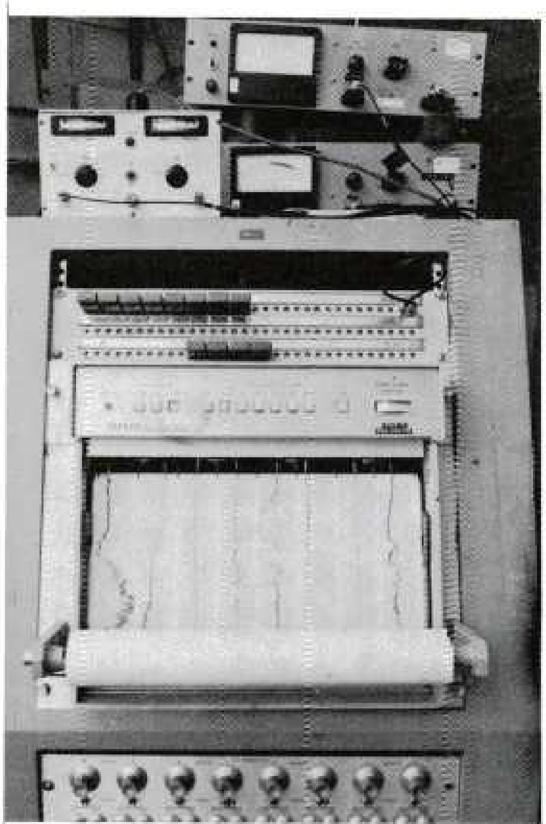


Figure 13 b.

8 channel Brush recorder used in the investigation

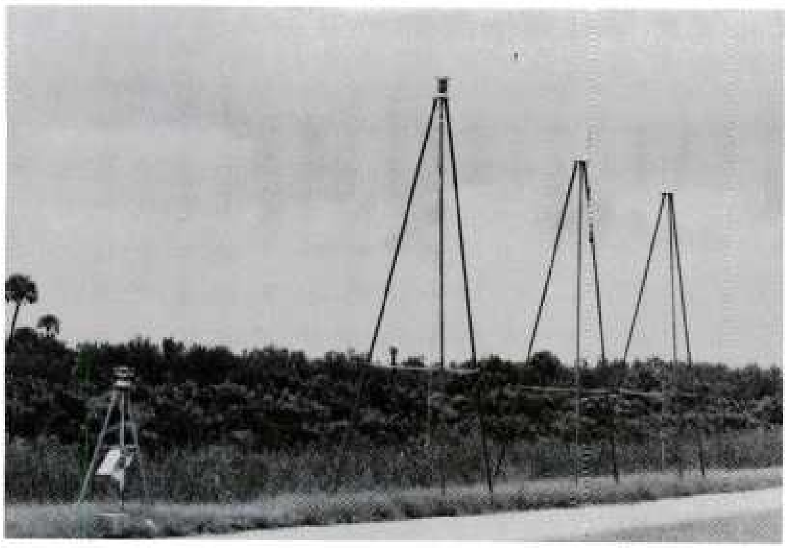


Figure 13 c.

Three 20 foot and one 5 foot tripods housing field mills and corona points

and had large enough separations between the collectors and ground that they were unaffected by rain. The wind speed anemometer was adjusted to give full scale deflection on the recorder for wind speeds of either 0-25 or 0-100 mph. The wind direction was plotted automatically on an adjacent channel. Corona discharge was measured by passing the conducting cable from each of the three corona sources through separate 100 ohm 1% resistors to a common ground source. The voltage across the resistors was measured with Hewlett Packard 413A DC Null Voltmeters which are capable of measuring ± 1mV full scale and amplifying to give a ± 1V extremely stable output on the Brush Recorder. With this approach corona currents as low as ± 0.2 μA can be measured. The use of common ground enables accurate comparison of corona current from different points.

Preliminary investigations at the site uncovered a possible problem with the earlier measurements of corona current from the dissipation array. The array had a resistance of 1000 ohms to the tower as the insulation at the top had broken down. The array ground was a different ground to the tower and ground currents of several tens of microamps could be measured. If these currents had been in existence for some time they could have influenced the earlier measurements as presented in the report to NASA(13). The earlier measurements could also have been influenced by pickup in the 3/4 mile cable feeding data back to the main site.

During the period of the experiment the corona points on top of two of the tripods were often changed. There were four types of points: a 2 ft 1/2" copper rod tapered off to a needle sharp point, a 1/2 inch diameter point, a 14 inch length of dissipation wire containing 16 barbs and an 8 foot piece of dissipation wire looped in a 2 1/2 foot diameter circle.

The recorder was an 8 channel Brush analogue pen recorder with chart speeds varying from .05 to 200 mm/sec which allowed excellent correlation of data.

5.3 Results

Let us first discuss the corona current from the extremely large dissipation array which contains approximately 1000 feet of a type of barbed wire. During the whole summer the maximum corona current from the array at 100 feet was only 38 μA. This value is in keeping with the currents measured throughout the years and reported by Chalmers in reference 6. At no time did we get any indication that the array was performing any differently from a single point. Extremely large displacement currents were often recorded, as one might expect, and there is a possibility that these spikes in the data recording have been erroneously taken in the past for corona current measurements. Such excursions are shown in Figure 14 superimposed on genuine corona currents of 0-20 μA. This figure shows the onset and decline of a short lived storm and also displays the potential gradient at ground level on which the lightning discharges and field build-up can be seen.

The behavior of a large umbrella array under high field conditions is no doubt very complex. One might consider that the field close to the edges of the array will be very large but our earlier discussions (S.K.L.) have

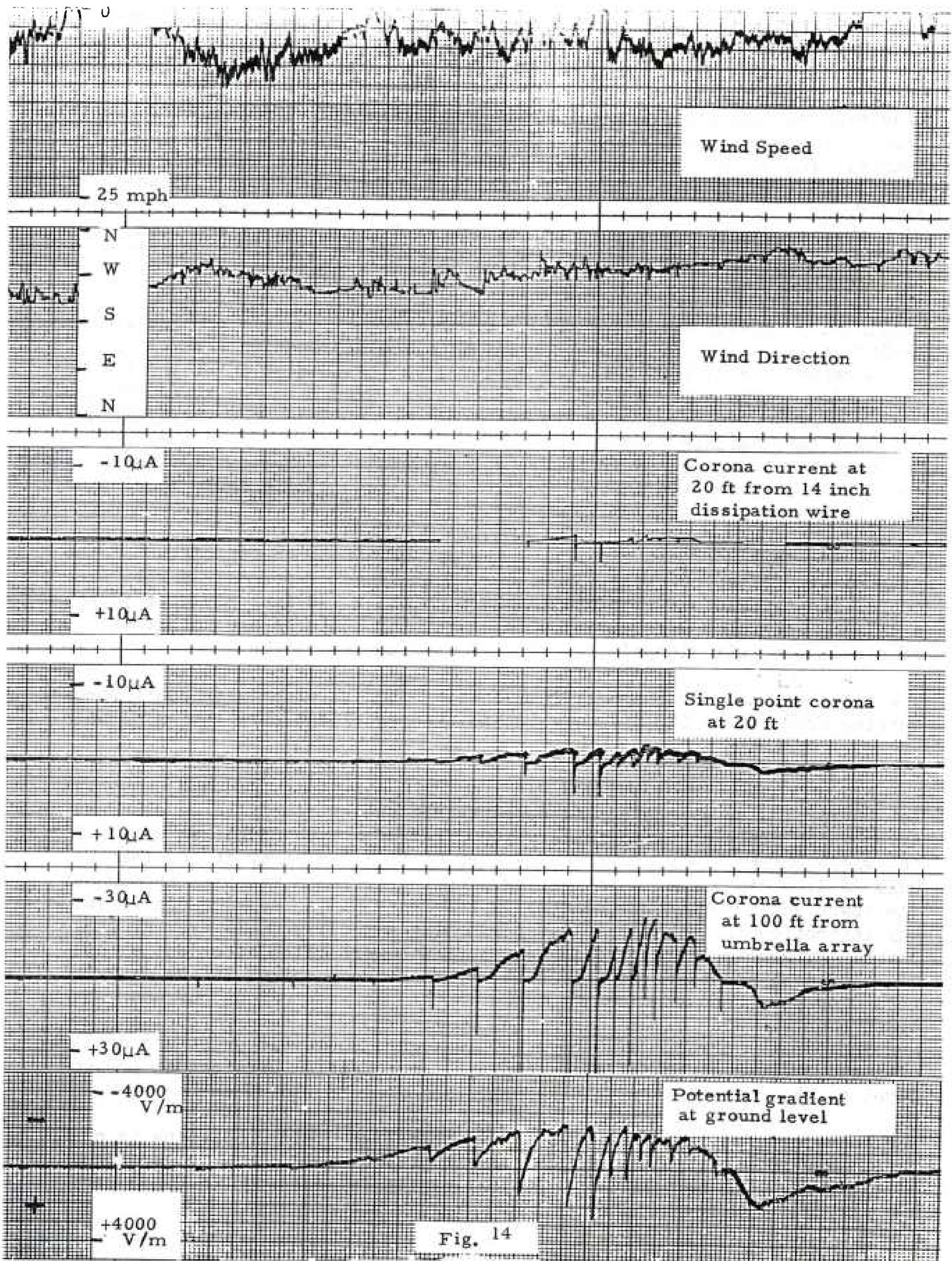

Wind Speed
25 mph
N
W
S
E
N
Wind Direction
-10μA
Corona current at 20 ft from 14 inch dissipation wire
+10μA
-10μA
Single point corona at 20 ft
+10μA
-30μA
Corona current at 100 ft from umbrella array
+30μA
-4000 V/m
Potential gradient at ground level
+4000 V/m

Fig. 14

shown that on top of the slightly spherical structure the field will be enhanced only by a factor of about 3. Corona will initially be given off from the perimeter of the array where high fields exist and this corona will probably be blown by the wind over the rest of the structure thereby reducing the field more, lowering the possibility for corona discharge. Only a small portion of the array may therefore give rise to prolonged and high corona.

Simultaneous with the corona discharge measurements from the dissipation array, Figure 14 compares corona from a single point with that from 14 inches of the same type of dissipation wire. This wire was comprised of 4 groups of four 2 cm long barbs. The results indicate that the single sharp point gives off approximately 50% more corona than the multiple point, which in turn gives off about 1/10 that of the dissipation array located at an elevation 5 times as high.

One may now argue that if 14 inches of dissipation wire emits 2/3 of the corona from a single sharp point then 21 inches would emit the identical amount and 42 inches would emit twice as much. Even if one doesn't expect a linear relationship it may be expected that longer lengths will emit more corona. In order to test this hypothesis an 8 foot piece of dissipating wire was wrapped in a 2 1/2 foot circle and placed on a tripod at 20 feet for comparison with corona from a single point. With the large circular configuration of the wire a higher field will exist around it than would be the case if it were spirally wrapped as in the umbrella array. The higher field would lead to more corona discharge.

Figure 15 shows some typical results of comparisons of data between the umbrella array at 100 feet, and the single point and 8 feet of dissipation wire at 20 feet. The umbrella array reaches currents of 35 A, which once more are about ten times greater than the values for the lower altitude single point. In this example the single point gives off approximately 50% more corona than the long length of dissipation wire. The maximum sustained currents were the order of 3 A from the single point and 2 A from the wire. The potential gradient during this time reached a value of -3000 V/m at the earth's surface and there was considerable lightning activity as evidenced by the large number of displacement current excursions. The single point, by virtue of its sharpness and elevation gave off corona of the order of 1/10 to 1/4 A under fair weather fields, whereas the umbrella array needed breakdown fields of 1100 V/m and the 8 feet of dissipation wire needed fields in excess of 2000 V/m for breakdown at a much lower altitude. At no time was there any indication that the 8 feet of corona wire gave off more corona than the single point.

Under high field and high wind conditions there were two occasions when the single point and the 8 feet of wire gave off similar amounts of corona. Such an example is shown in Figure 16. One can also see that the breakdown point occurs at a much lower potential gradient for the single point than the multiple point. The effect of the breakdown potential is more noticeable in Figure 17 where the field remains at a level just below that required for the 8 foot of dissipation wire to go into corona discharge.

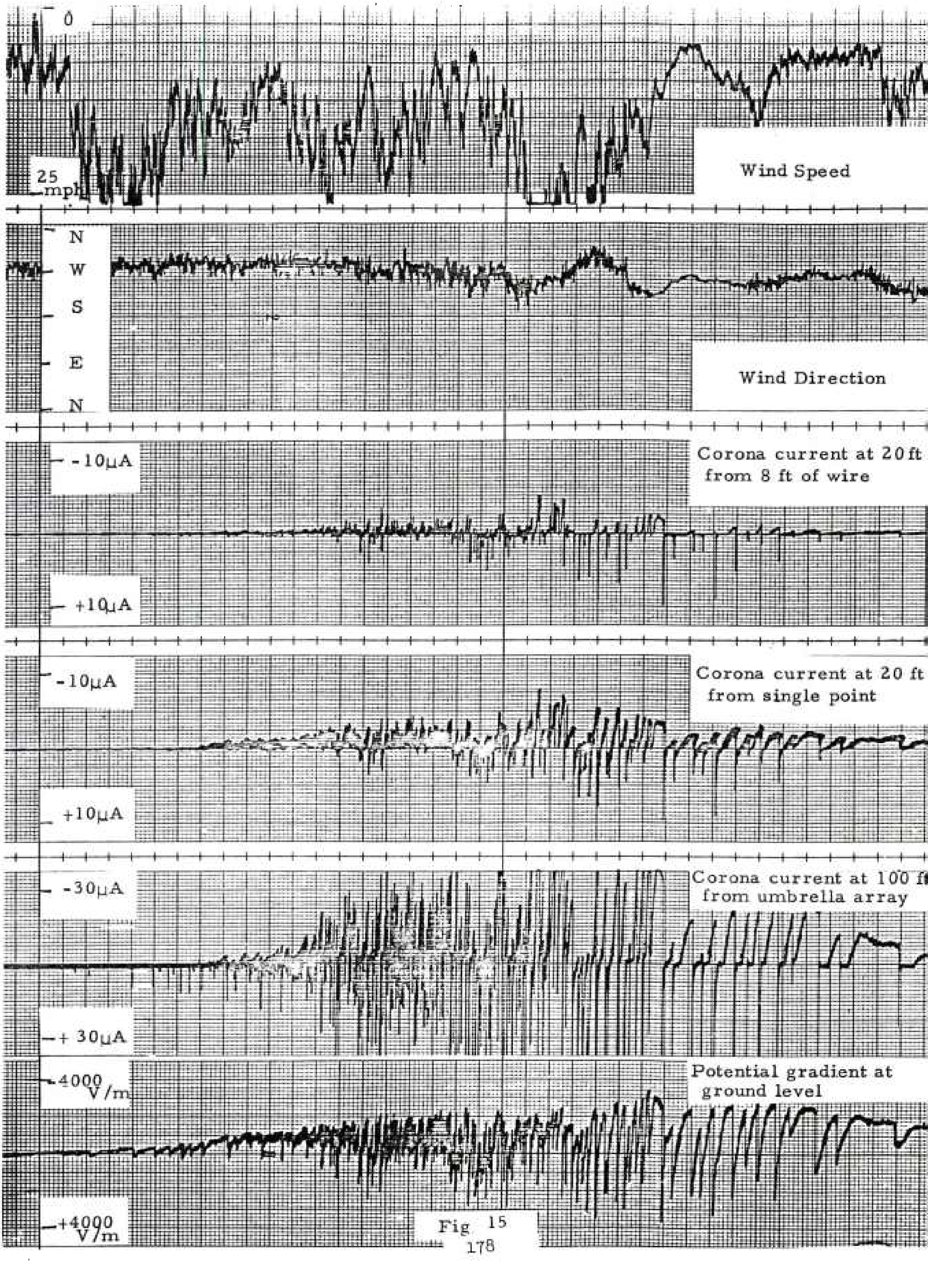

0
25 mph
Wind Speed
N
W
S
E
N
Wind Direction
-10μA
+10μA
Corona current at 20 ft from 8 ft of wire
-10μA
+10μA
Corona current at 20 ft from single point
-30μA
+ 30μA
Corona current at 100 ft from umbrella array
-4000 V/m
+4000 V/m
Potential gradient at ground level

Fig 15

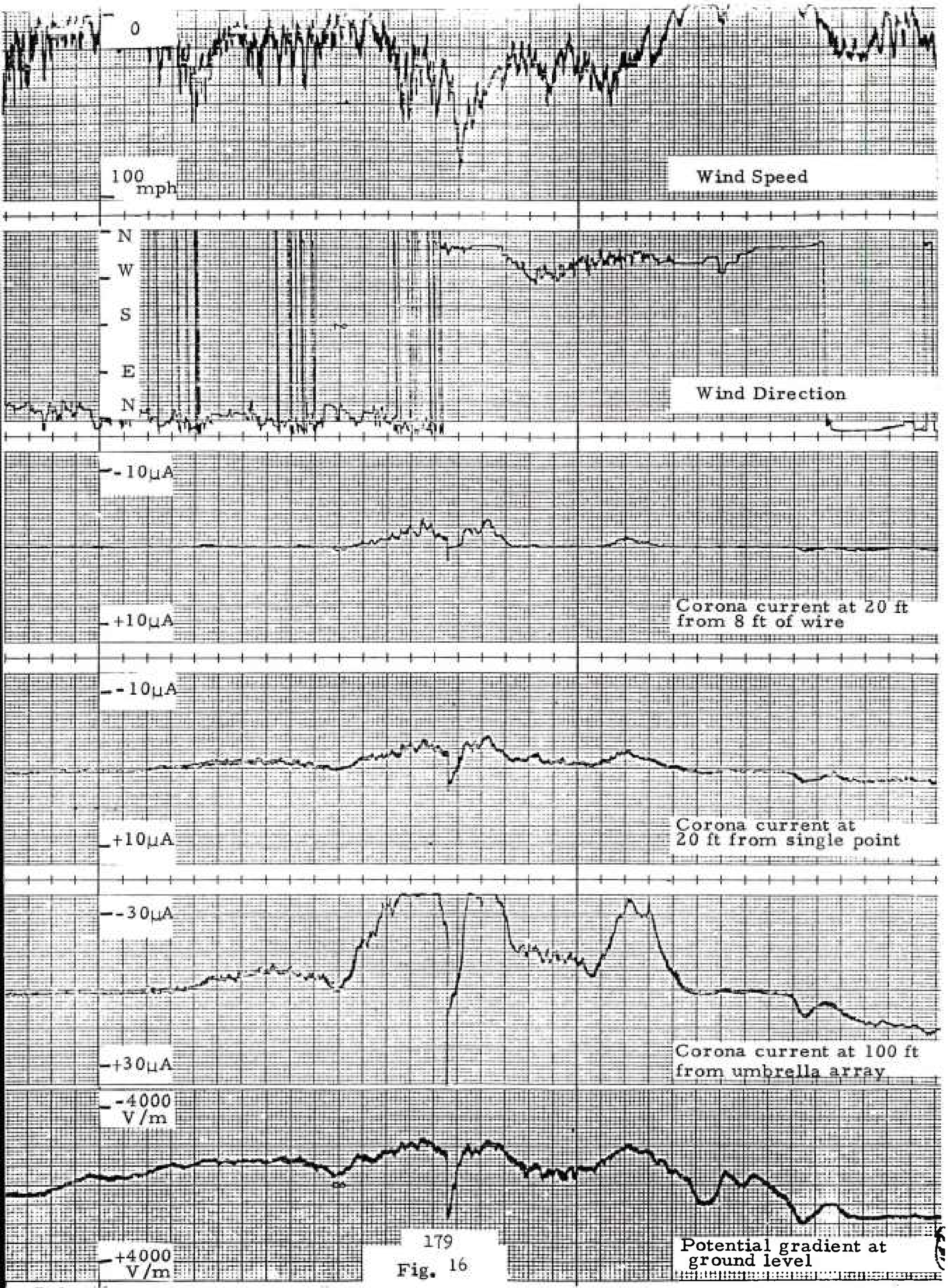
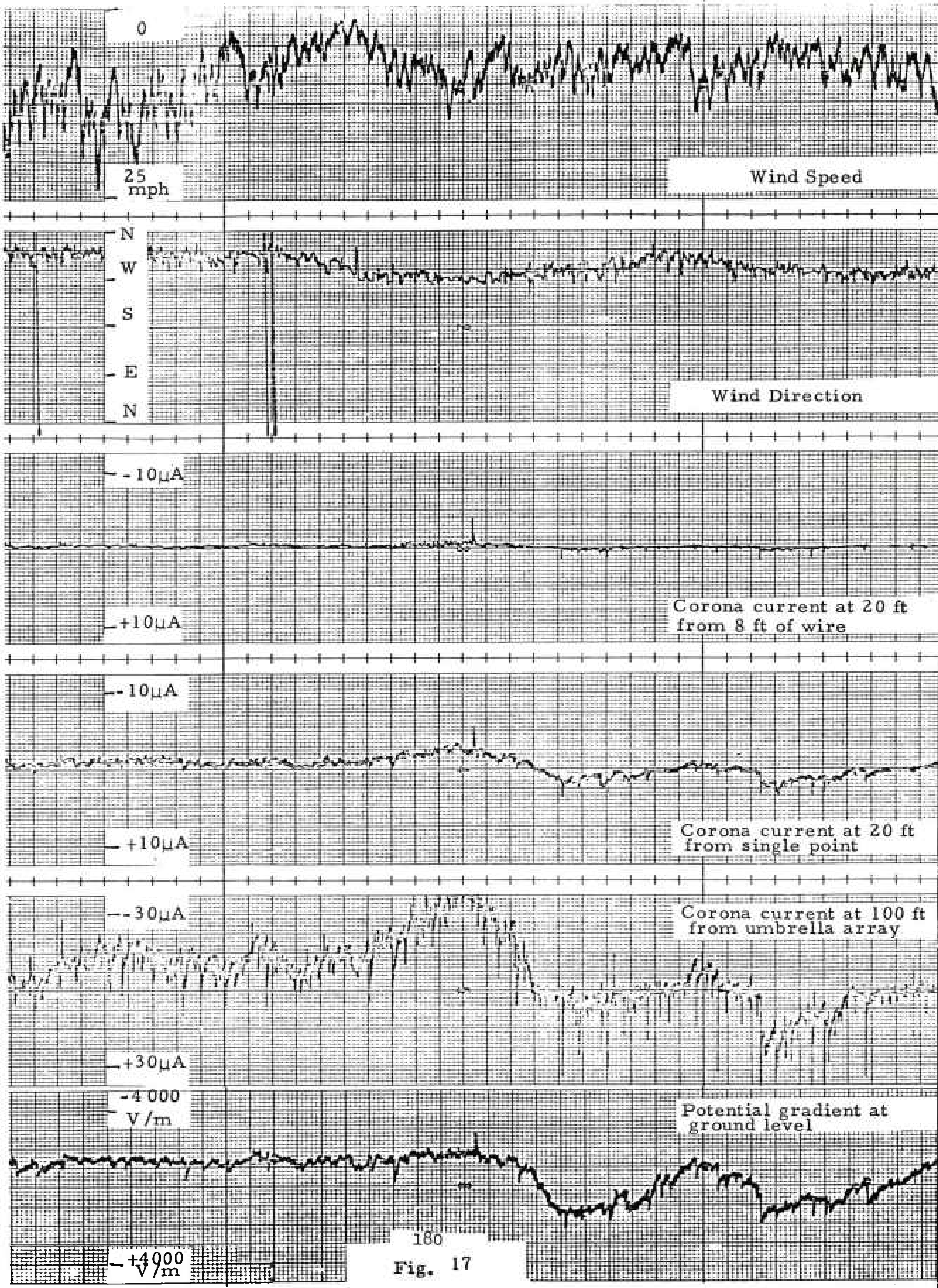

0
100 mph
Wind Speed
N
W
S
E
N
Wind Direction
- 10μA
+10μA
Corona current at 20 ft from 8 ft of wire
- 10μA
+10μA
Corona current at 20 ft from single point
- 30μA
+30μA
Corona current at 100 ft from umbrella array
-4000 V/m
+4000 V/m
Potential gradient at ground level

Fig. 16



0
25 mph
Wind Speed
N
W
S
E
N
Wind Direction
- 10µA
+10µA
Corona current at 20 ft from 8 ft of wire
- 10µA
+10µA
Corona current at 20 ft from single point
- 30µA
Corona current at 100 ft from umbrella array
+30µA
-4 000 V/m
Potential gradient at ground level
+4000 V/m

Fig. 17

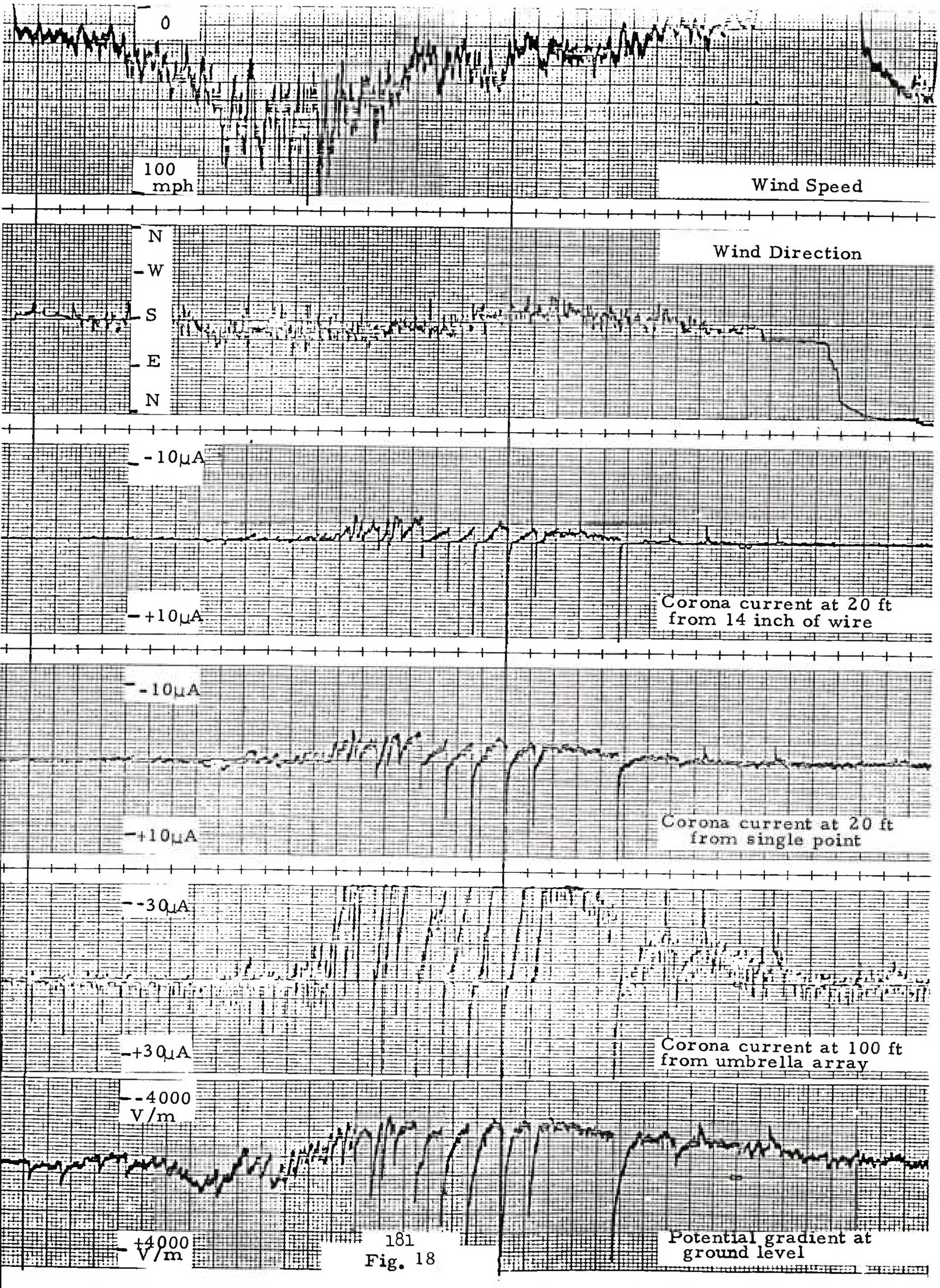

0
100 mph
Wind Speed
N
W
S
E
N
Wind Direction
-10μA
+10μA
Corona current at 20 ft from 14 inch of wire
-10μA
+10μA
Corona current at 20 ft from single point
-30μA
+30μA
Corona current at 100 ft from umbrella array
-4000 V/m
+4000 V/m
Potential gradient at ground level

Fig. 18

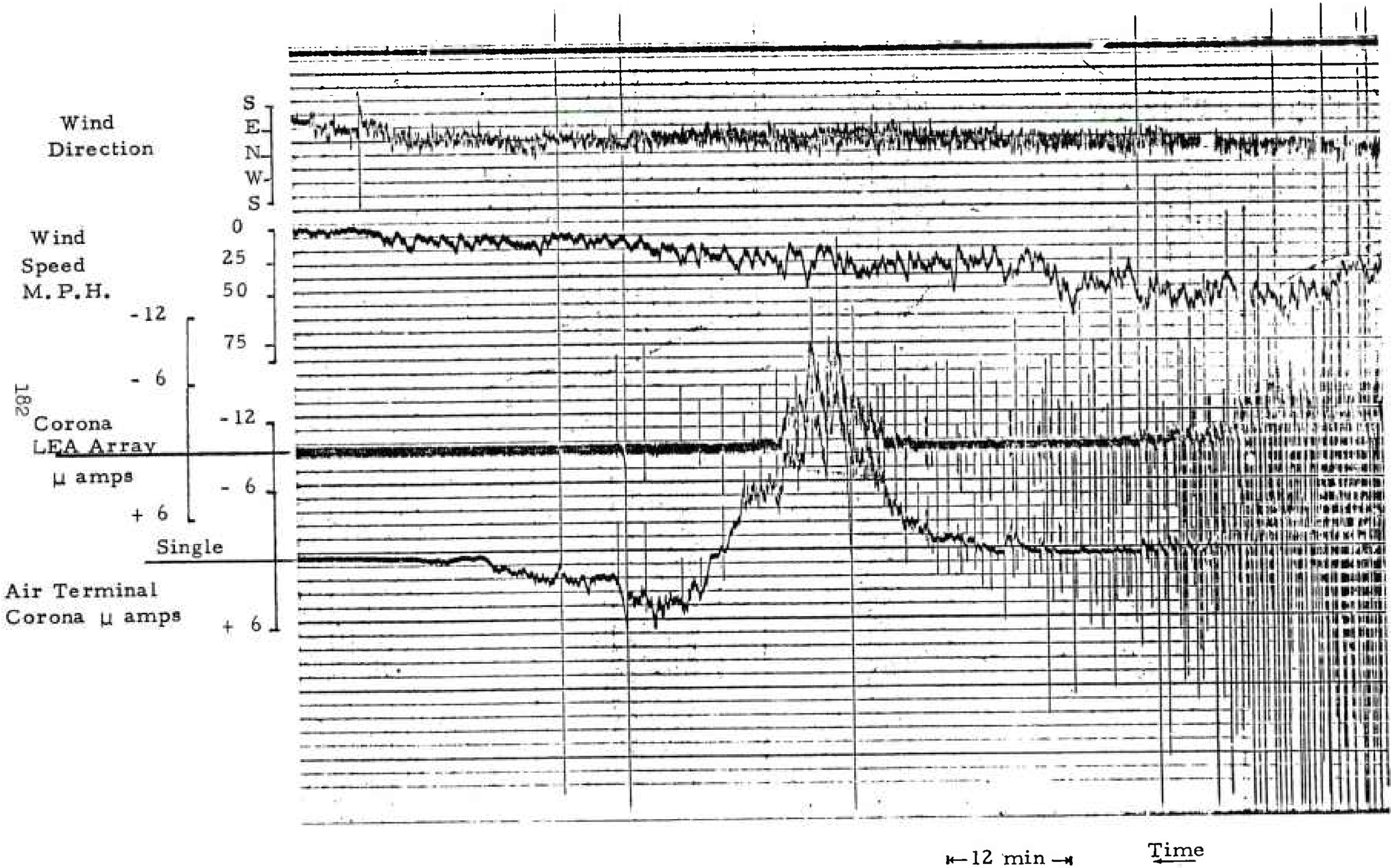


Figure 19. Corona Current Results from LEA Array and Single Air Terminal

The 14 inch piece of dissipation wire also on one occasion gave corona currents similar to the single point. Again, this was under high field and high wind conditions as displayed in Figure 18. Throughout the summer thunderstorm season there was no occasion when the single point gave off less corona than a multiple point at the same height. In general the 14" and 96" dissipation wires gave off similar amounts of corona at levels approximately 1/3 less than the single point.

Once more, the maximum corona current measured from the umbrella array was under 40 A. The single point at a much lower altitude gave a maximum value of about 5 A. These values are in keeping with the many investigations of corona current taken in the past by many scientists as referenced earlier.

The 1/2 inch blunt point never went into corona which was visible on the chart moving at about 6 inches per hour. Displacement currents were obviously visible and there may be a possibility that occasional sudden extremely high values of electric field may have given rise to corona from this blunt point but the chart speed used for most of the data did not allow such observations.

These results do not support claims that many mA of corona current is emitted from these arrays. One point that could not easily be proved at this site however was that a single point gave off more corona current than a dissipation array at the same height. Fortunately a Central Florida company provided such an array and two 50 foot wooden poles for a comparison test. The array was a circular panel array approximately 6 feet in diameter and was the same one that had been offered for sale to the Florida company for protecting a power facility. This array was placed atop a 50 foot wooden pole and connected to ground through a 10 ohm 1% resistor. Another 50 foot wooden pole some 300 feet away housed a single sharp copper point identical to a lightning rod air terminal and connected to the common ground through a separate 10 ohm 1% resistor. The voltage across these resistors was monitored on a Honeywell Visicorder along with wind speed and direction. The results again agreed with scientifically accepted belief. At no time did the corona from the flat panel dissipation array exceed that of the single point.

Figure 19 illustrates the largest currents that were recorded at both the array and the single air terminal. The thickness of the basic trace on the array record is due to 60 cycle pickup and the large sudden excursions are due to displacement currents when lightning occurs. When the wind speed increases and large currents are flowing, then a further increase in the corona current is evident. In this case the wind direction is such as to cause no space charge interference between the two instrumented poles. At the beginning of the record a severe storm is in progress with many discharges, but the corona current from the array does not exceed 6 A. As time progresses the displacement currents get somewhat smaller as the lightning becomes more distant, but the field increases as a new charged cell passes overhead. It appears that three lightning discharges resulted from this cell and caused three very large displacement currents. In these high fields the air terminal current yields up to 14.5 A; whereas the array current only reached 8.5 A. The array only went into corona when the air terminal was dissipating 6 A. After this the rate of increase of the array current was the same as the air terminal. This means the array is unlikely to give more corona than the air terminal, even in the extremely high fields of the downward coming leader. Further results at this facility demonstrated similar effects.

NASA/KSC personnel also measured the corona current from a panel type dissipation array on top of a 500 foot tower at KSC and found that the value throughout the summer thunderstorm season remained below 200μA. This array was also struck by lightning (Figure 11).

It must thus be concluded once more, that a single point gives more corona discharge than a multiple point and more than the dissipation arrays under test. A single point is therefore a much better dissipator of ions and if one must believe in cloud charge dissipation or a protective ion cloud, then a single point should be the main dissipator and not multiple points. A further striking but not unexpected conclusion is that natural corona from the nearby vegetation as measured by field mill space charge techniques between 0 and 100 feet, was found to be an average 1μA per tree under severe thunderclouds. It may therefore be argued that the 30 or so palm trees cleared for the erection of the 100 foot collimation tower would emit the same corona current as the 1000 feet of dissipation wire placed at the top of the tower.

6.0 PHOTOGRAPHIC AND CORONA INVESTIGATIONS OF AN ARRAY ON A 1200 FOOT TOWER

6.1 Site Description

Site C-9, Eglin Air Force Base, Florida was chosen for this investigation because it houses a 1200 foot tower which should be struck by lightning more than 40 times per year (see Section 4.0). The tower also supported a 19-foot diameter umbrella type dissipation array which was replaced in April 1974 with three 6 feet x 4 feet panel arrays placed parallel with the ground and some dissipation wire at the edges of the panel on a framework making an angle downward from the array. Reports had been published [11] that indicated the tower had not been struck by lightning in the first 18 months after array installation.

Figure 20a is a photograph of the 1200 foot tower; Figure 20b shows a view of the panel arrays. Close examination shows the dissipation wire at the edge of the array. Figure 20c is a downward view of the panel array showing the sharp 4 cm spikes.

6.2 Instrumentation

Magnetic links were placed on the downlead from the array some 3 feet below the top and also at the bottom of the tower on the same downlead. The 3 ferrous links in each 65 cm arm were placed at 13, 26, and 62 cm from the conductor. Once the links are de-gaussed a current between 5,000 and 200,000A will cause magnetization of the links which in turn can be measured and the intensity related to the lightning current. Should there be multiple strokes only the peak value will be recorded. By placing three links at various distances in each arm more accurate measurement of current are allowed as the magnetic intensity is a function of distance from the conductor.

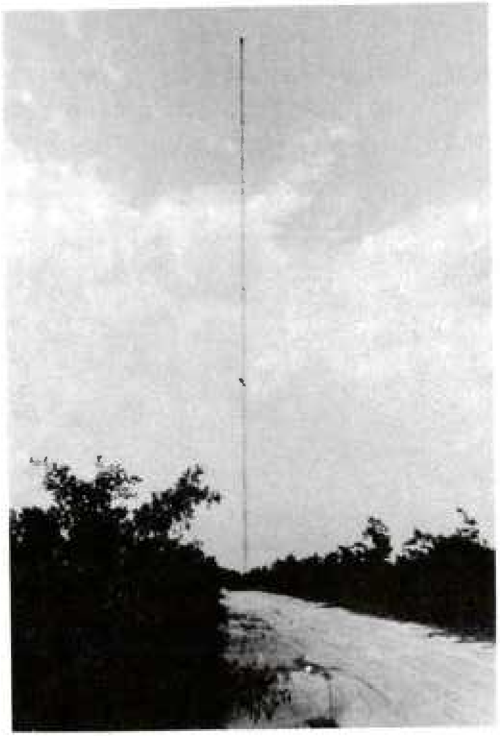


Figure 20 a.

1200 foot tower, Eglin A. F. B.
Florida site C9

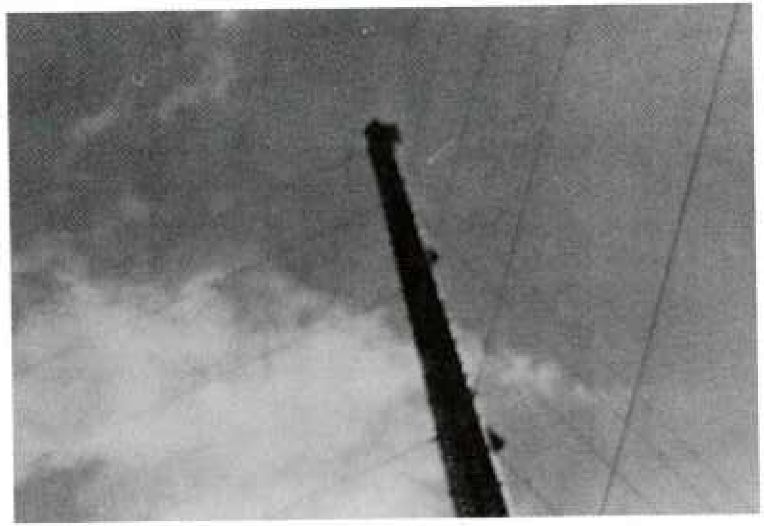


Figure 20 b. View of the top of the 1200 ft tower showing the panel arrays

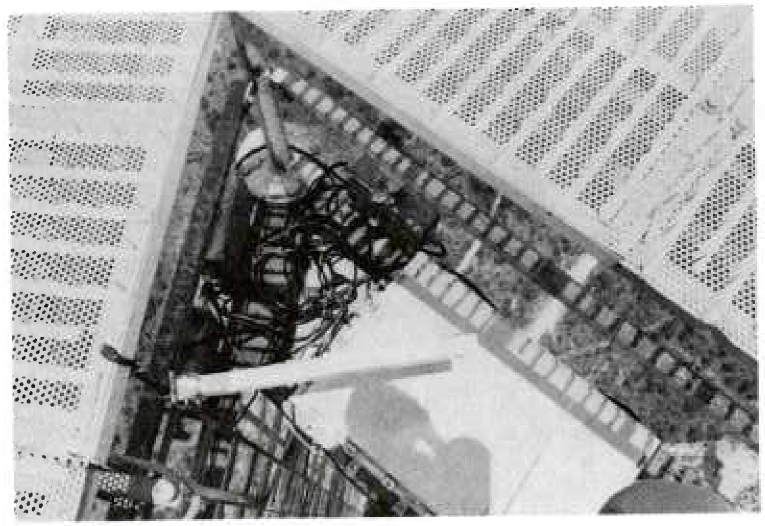


Figure 20 c. View down the middle of the 1200 ft tower showing the magnetic link arm

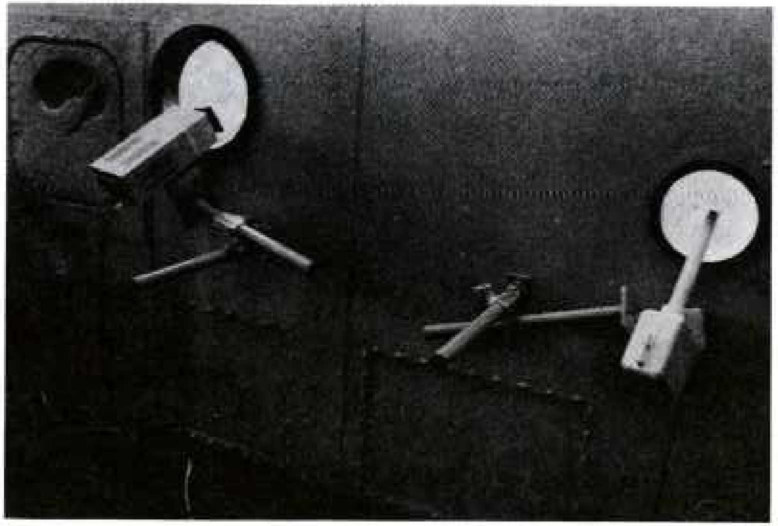


Figure 21 a.

Silicon diode video camera and lightning transient detector in the trailer at site C9, Eglin A.F.B. looking at the 1200 ft tower

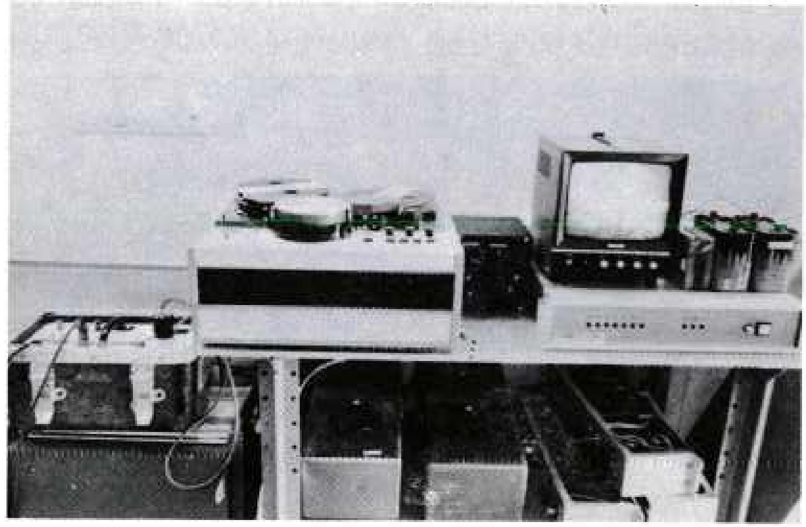


Figure 21 b. Recording equipment installed in the trailer at site C9, Eglin A.F.B., Florida

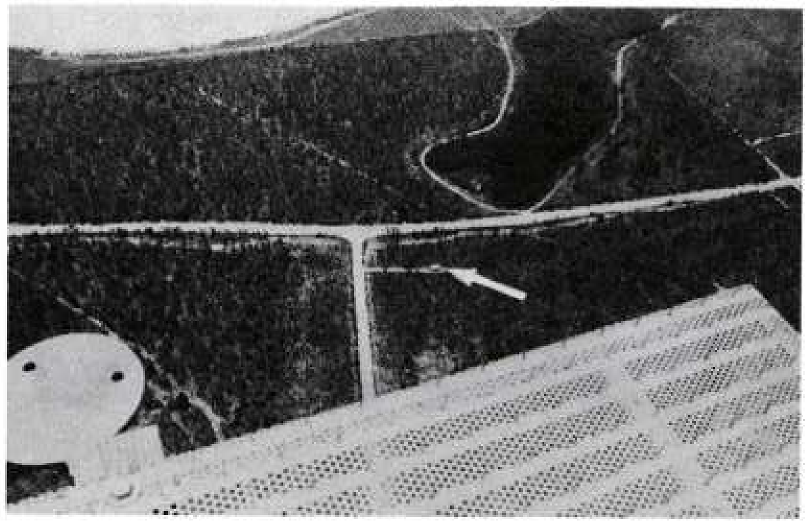


Figure 21c. The equipment trailer viewed from the top of the 1200 ft tower

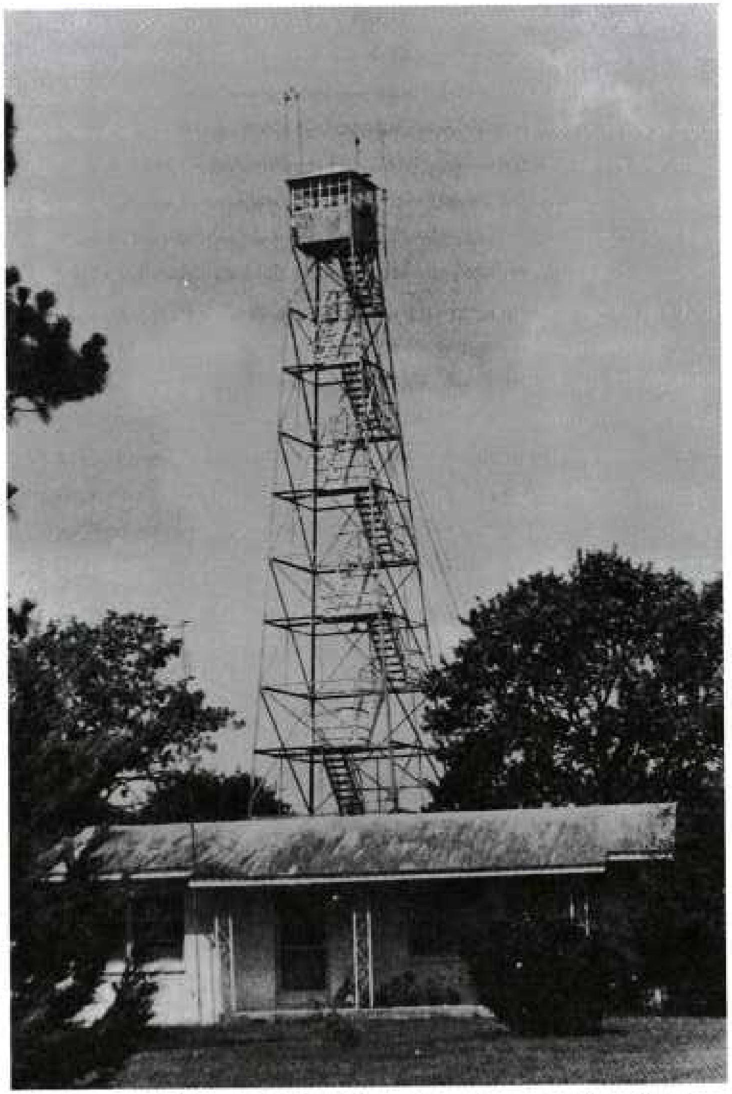


Figure 22 a. 100 ft forestry tower 4 miles west of the 1200 ft tower

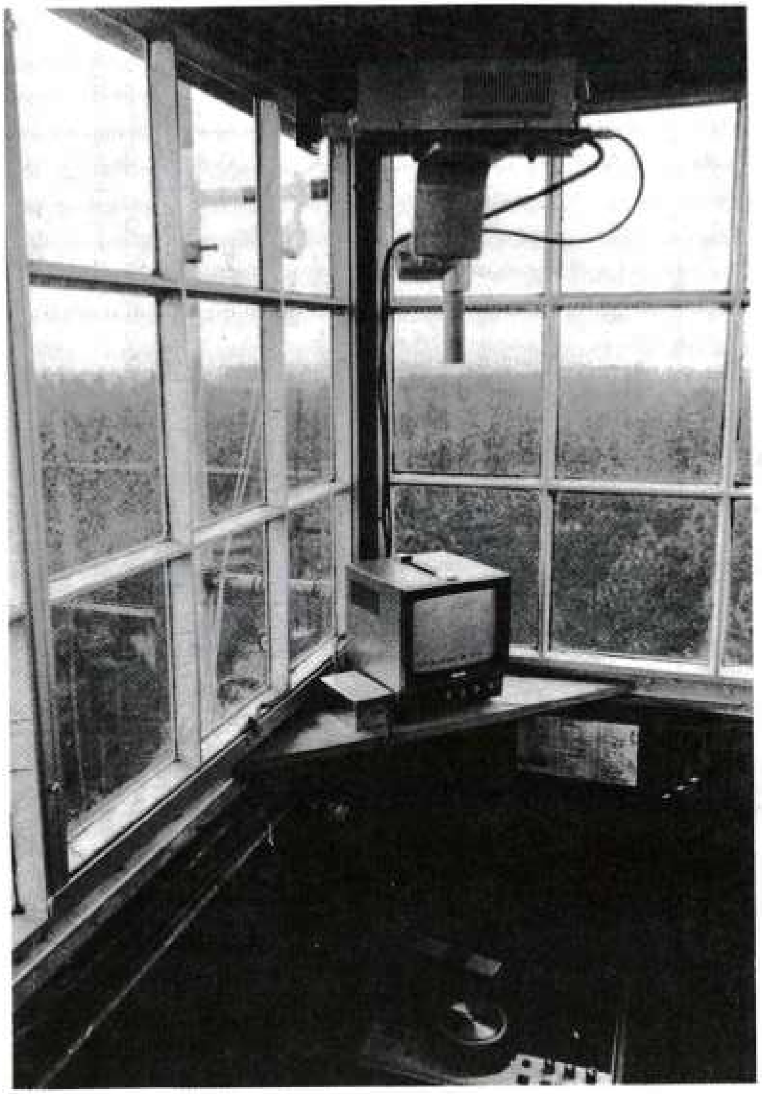


Figure 22 b. Video equipment installed in the forestry tower

The positioning of the two arms was not ideal for monitoring current from the lightning strike as it was unlikely that the number 6 copper wire from the array would be carrying all the current if the array had been struck. In fact, most of the current would probably pass down the tower structure. The magnetic link data would, however, act as an indicator that lightning had struck and give some idea of the order of magnitude of the current. In later tests when a single lightning rod was put up, it would give accurate measurements of peak current. A magnetic link arm is shown in photograph 20c

At the base of the tower the array was grounded through either a 10 or 100 ohm resistor to an excellent ground and the corona current monitored after amplification with a Hewlett Packard DC Null Voltmeter. An RSA-10 lightning flash counter (ref. 19) was installed near the base of the tower. The unit had a 4 m whip antenna and whenever lightning occurred within about 15 miles a signal was put on the chart recorder. This gave an indication of storm days for later correlation with lightning incidence data.

In order to examine lightning incidence to the tower, video photography was installed at a trailer some 1200 feet south of the tower and at Rockhill forestry tower some 4 miles west. The video equipment incorporated silicon diode cameras, time code generators and remote control video tape recorders. Silicon diode cameras were used because they cannot be damaged by looking into the sun, they have a much wider visible spectrum than vidicon cameras and their retention capabilities are good if used in a slow motion mode. They are extremely sensitive and can be made to bloom if the source is very bright. The time code generator was modified to provide it with an external battery source. This modification was necessary because of the remote position of the site and the constant short lived breaks in the power which could modify the accurate time code information.

The silicon diode camera in the trailer was focussed on the tower through a wide angle lens with remote controlled iris that looked at the tower through a porthole in the trailer as shown at the left hand side of Figure 21a. The recording equipment is shown in Figure 21b and the position of the traile as viewed from the tower is shown in Figure 21c. Figure 22a shows the 100 fc Rockhill forestry tower and Figure 22b shows the video equipment in position. A telephoto lens was used in this camera to focus the image on the 1200 foot tower.

At the Rockhill tower the video equipment was turned on manually whenever storms were in the area, but at the trailer site the video equipment was turned on automatically. A microwave telephone link from the weather office at Eglin Air Force Base to the C9 tower was used to automatically switch on the video equipment whenever a storm was believed to be in the vicinity of the site. Unfortunately the equipment was often damaged at site C9 when diodes in the automatic control equipment were blown by line surges. These lines went only from the microwave antenna on the tower to a building some 30 feet away and the damage indicated that surges came in on these lines and not the power lines. It is strongly suspected that at least four outages were caused by lightning strikes to the tower effecting the automatic switch on circuitry. Because of the many malfunctions in the communication lines considerable storm activity at C9 was not recorded.

An optical lightning detector was placed in the trailer for observing discharges close to the tower top. Figure 21a shows this detector looking through the right hand porthole. The detector responds to very fast light transients and it was trained on the tower top by using a long narrow tube. Reflections of lightning from clouds in the field of view are detected as well. The data was recorded and it also was used to activate an oscillator and put a signal on the audio channel of the video recording in order to help in locating discharges on the videotape.

Problems were also encountered with surges passing down the lines running from the base of the tower to the trailer. Surge protection was added to these lines, but at times diodes were damaged and equipment stopped. These surges could only have come in from the tower as the power line was isolated and came from a different direction.

6.3 Lightning History at the Tower

The 1200 foot tower was made operational on 28 September 1967. The tower was often used for Air Force missions and related equipment was placed close to the top of the tower.

During the next few years periodic lightning damage occurred and a list of this damage and lightning related events is shown in Appendix 1. As a result of this damage, LEA were contracted to install one of their dissipation arrays atop the tower. Their work was initially completed on 1 September 1972 and a new ground loop system was installed a few days later. On 30 Sept. 1972, there were two direct lightning hits to the array which caused visible damage to the recorder measuring dissipation current. On 13 Oct. 1972, a short to the tower was found in the #6 downlead from the array and on 17 Oct. 1972, the amplifier cards were found to have been damaged by lightning from a recent storm.

Damage discovered on 2 Jan 1973, indicated more lightning strikes as did the multiple damage discovered on 4 June 1973 and the damage of 18 June, 29 June, and 2 July. After further damage in Feb. 1974, when part of the array was burned, LEA returned and decided to install a new array which they said was to prevent lightning hits from the side. This new array was installed on 22 Apr 1974.

On 21 May 1974, there was possible evidence of a further lightning strike and within the next few weeks lightning damage was found in the array ground wire.

Log book evidence also indicates low current dissipation from the array (29 Sept. - 10 November), even though the recording instruments were 100 μA full scale.

It is obvious that there has been much lightning damage to the tower even if some of the log book data erroneously listed lightning as a problem. Visual observation of lightning hitting the tower and vaporized #6 copper wire are good log book indications of lightning. As the log book dates progress it

appears that the site personnel were becoming more aware of various facts that reduced the probability of lightning damage. The main points here were to check the continuity of the ground line and to switch off all equipment during storm conditions or at times when the site was not manned. Ground resistance checks were made very often from 1972 onward, but these are not listed in the Appendix.

The log books certainly indicate much damage to the pump in the well area and a number of occasions where the ground wire was damaged. The ground line between pump and tower was found to be non-conducting on 19 Jan 1972 and was repaired. Shortly afterward, a #12 insulated wire was run from tower to the well in order to enable a continuity check to be performed easily between tower well and tower. This return wire was later found burned and replaced in June 1973. The ground wires had to be dressed up occasionally to keep the continuity good and the ground return to the main power pole was rewired in October 1974. The incoming power line ground to the main power pole was seen to be considerably damaged in September 1975 (Figure 23). Also, LEA accidentally cut through the ground wire in September 1972 and presumably corrected it.

The number of times the ground wire was found to be defective certainly implies that this was a significant factor in some, if not most, of the lightning damage. Another significant factor was the log book entry of October 1972, saying that many circuits were turned off for at least 50% of the nights since installations the previous year.

This history of lightning problems at Eglin only covers the period to June 1974. The summer of 1975 has been thoroughly investigated by Atlantic Science Corporation.

The history of the tower ground is a little unsure for the first few years of existence of the tower, but enough information has been gathered from the log books to cast considerable doubt on their being a good ground system prior to the installation of the array. This information is again listed in Appendix 1. It is highly likely that the grounding problem could well have led to the considerable early damage, but when the problem was corrected and constantly monitored, the majority of lightning incidence problems were eliminated. A look at the grounding situation and discussions with site personnel clarified this suggestion.

6.4 Site Grounding

During the summer of 1975, Atlantic Science Corporation found the resistance of the tower from top section to bottom section to be 0.22Ω, implying that the sections of the tower were reasonably well connected to one another and that the grounded array wire did not significantly change the grounding situation at the top of the tower. It had previously been thought that if lightning struck a tower top that was not at ground potential the high current may pass through an instrument line near the tower top that would have a better ground connection, hence causing equipment damage. This could be the case if the tower was not well grounded and the instruments power ground was of lower resistance. An examination of the facts indicates that this may often have been the problem.

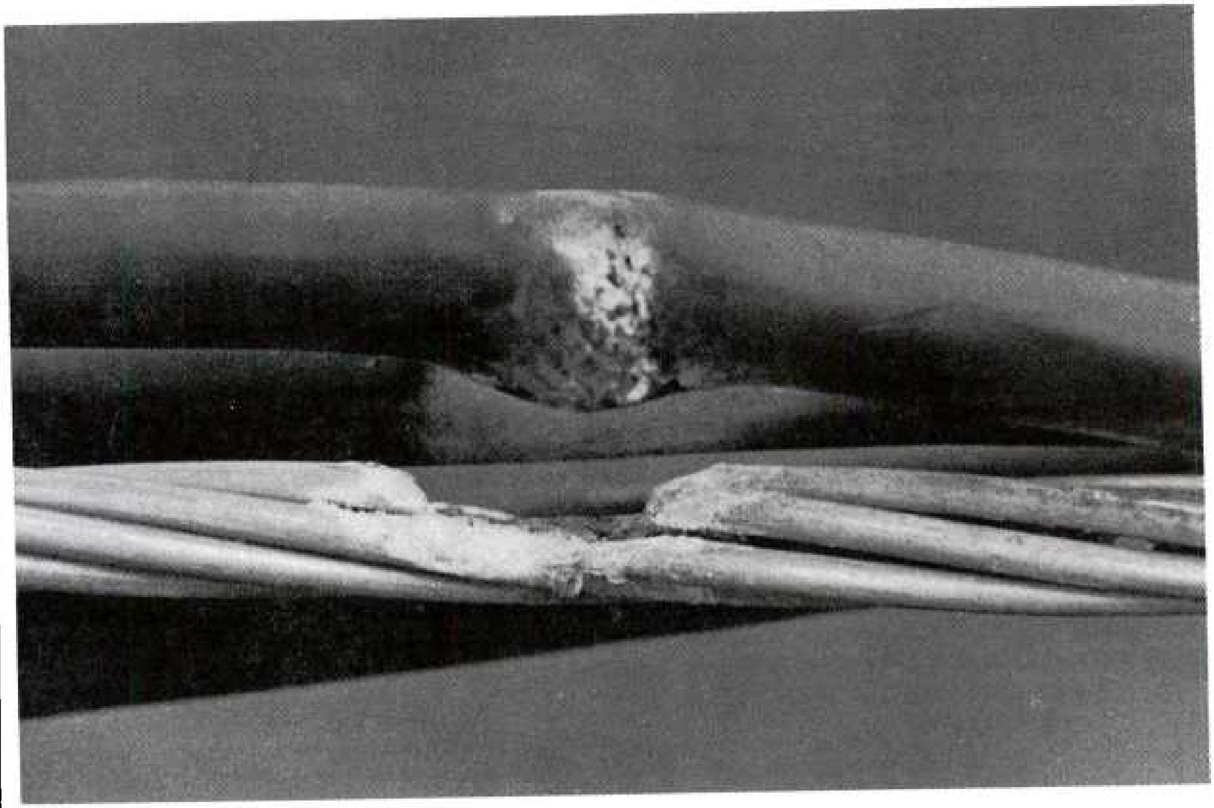


Figure 23

Power line damage caused by lightning

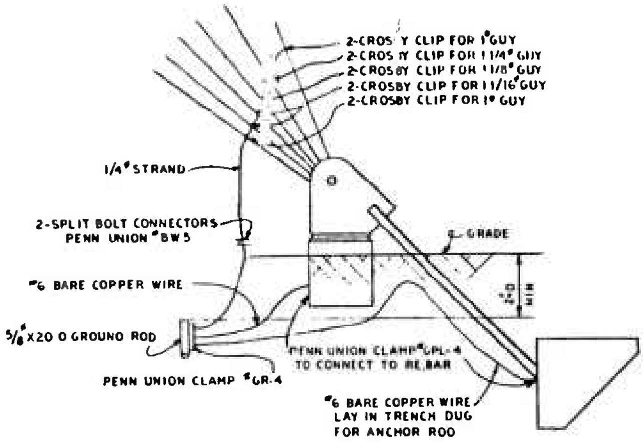
The original grounding system for the tower has two 20 feet by 5/8 inch inter-connected copper ground rods at the tower base and one at each of the three guy bases as shown in Figure 24. The low resistance of these rods to ground in the sandy conditions of Eglin is questionable, and in order to test it a 3 inch by 10 ft XIT copper ground rod was placed in the ground a few hundred feet from the tower. During a number of months and some extremely heavy rains its resistance was measured by FAA and USAF personnel to be some 170 ohms. This implies that the resistance of the original tower ground rods was also high.

The log book however indicates that by Jan. 1972, a wire was connected from the tower ground to the 285 foot deep well some 150 feet from the tower. This well ground has been measured by FAA and USAF personnel and found to be between 1 and 3 ohms to ground which is considerably better than the copper rods. This implies that whenever the line between tower and well was damaged, lightning current would probably pass down instrument lines to power lines and other better ground connections causing havoc along the way. Prior to the stranded wire being laid to the well in 1972, the copper water pipe was used as a ground and was at times found to have poor continuity due to corrosion. On 5 Sept. 1972, the ground network was improved by the array manufacturers and nine 6 ft x 5/8 inch copper ground rods were connected to the tower and well grounds as shown in Figure 25.

A conversation with Mr. W. B. Evans, who manned the C-9 site at Eglin for many years, indicated that he was aware of a grounding problem. Apparently in July 1969, it was discovered that the copper pipe that ran between the tower building and the well had a 45Ω resistance due to corroded connections. He stated that on one occasion lightning burnt a hole in the well pipe the size of a finger. Some six months later a braided copper wire was buried between the well and the tower where it was connected to the tower and power ground line with an aluminum link. Mr. Evans indicated that the damage during the years 1971-73 was considerably reduced to only those times when a strike had damaged the ground line. If this line was good he reported very little damage. The site personnel were eventually instructed to check this line frequently.

In reference to the dissipation array, Mr. Evans said he was on hand when lightning hit the array twice within a minute shortly after its installation. He said the first strike burnt the recorder, but the second one blew the array series resistor and capacitor to pieces. He reported that his hand was slightly burnt, as it was near the explosion and that the manufacturers claimed that lightning did not strike the array.

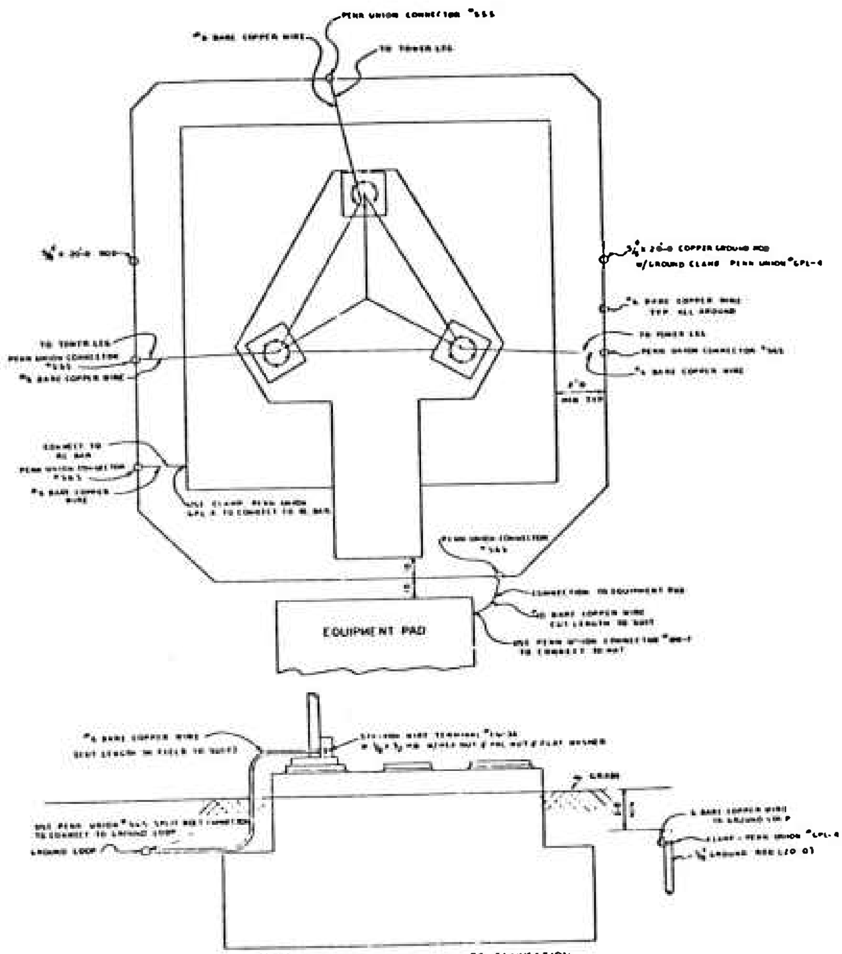
With the detailed analysis of the log book history and the grounding system it appeared that lightning would still strike the array but little damage would result because of good grounds. The video photography was set up to investigate this suggestion.



TYPICAL GUY CONNECTION

GROUNDING NOTES:

1. ALL REINFORCING BARS WILL BE TIED SECURE TO ASSURE CONTINUITY BETWEEN EACH BAR.
2. TO INSURE CONTINUITY BETWEEN ALL LEVELS OF REINFORCING BARS, EACH LEVEL WILL BE TIED ACROSS BY A VERTICAL BAR.



ELEVATION SHOWING TYPICAL LEG CONNECTION

Figure 24. Original grounding of 1200 foot tower base and guys

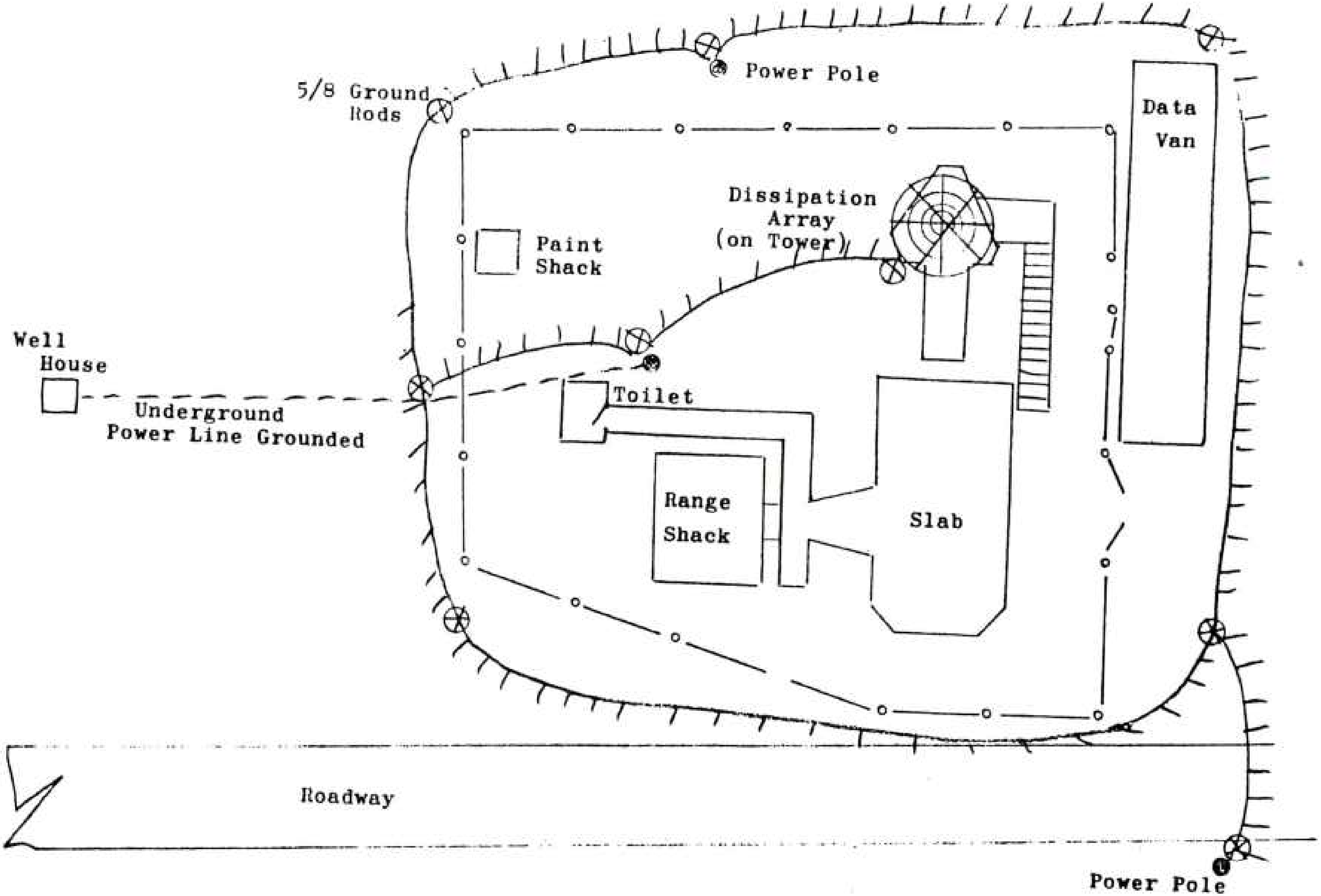


FIGURE 25. Improved grounding at site C9 during array installation

6.5 Results

6.5.1 Corona Current

The initial investigations on the array showed that it had a resistance to the tower of about 3k ohm which gave rise to "Telluric" or ground currents of the order of 150μA due to the differing ground configurations. An indication that such an effect was occurring during the corona recording period discussed in reference (12) was shown in the log book recording of 20 Dec 1972, when a resistance check gave different values with the meter leads reversed. Corona dissipation could be a reason for this, but ASC tested the resistance by AC and high current DC means and showed conclusively that ground loops existed. These were probably a function of power ground to the top of the tower, a poorly insulated array and the tower ground.

Professor Olsen of the University of Minnesota measured corona currents from the array atop the 1200 foot tower and maximum value he recorded was of the order of 300μA under high field conditions. Maybe the Telluric currents were there at that time, which indicates that perhaps the maximum corona current should have been of the order of 450μA; a figure again in keeping with the values expected for a tower of this height.

The dissipation array was removed from the tower during the summer of 1975 and replaced by a 10 foot 1 inch copper lightning rod with a sharp point. The rod was well insulated from the tower with teflon, and corona current was measured by monitoring the voltage across a 10 or 100 ohm resistor in the line between the copper point and the well ground. A typical record of corona current, optical detector data and electromagnetic lightning flash data is shown in Figure 26. During stormy conditions the single point current often reached values of several hundred μA and the largest recorded was 720μA. This value is considerably more than the maximum monitored by Professor Olsen from the array which in turn was more than that monitored by us from the array. Values of array corona current were obviously hampered by Telluric currents in the grounding circuit, but at no time were any steady values recorded which approached the values in excess of 150 mA reported in reference (12). One wonders if displacement currents were erroneously interpreted as corona current on those occasions. At no time were Telluric currents part of the current measured from the single point.

It is interesting to note that the line between the resistor at the base of the tower and the corona recording device was occasionally subject to very short lived high currents which gave rise to heat bubbles in the wire; a feature one would expect from lightning currents passing down the tower. A further point of interest relates to the value of the resistance in the line between the corona point and ground. With a resistance of 10^6 ohms in the line and with 100μA one would only lose 100 volts. The high electric field on top of the tower is enormous compared to this value and so grounding should not effect the corona current in any way.

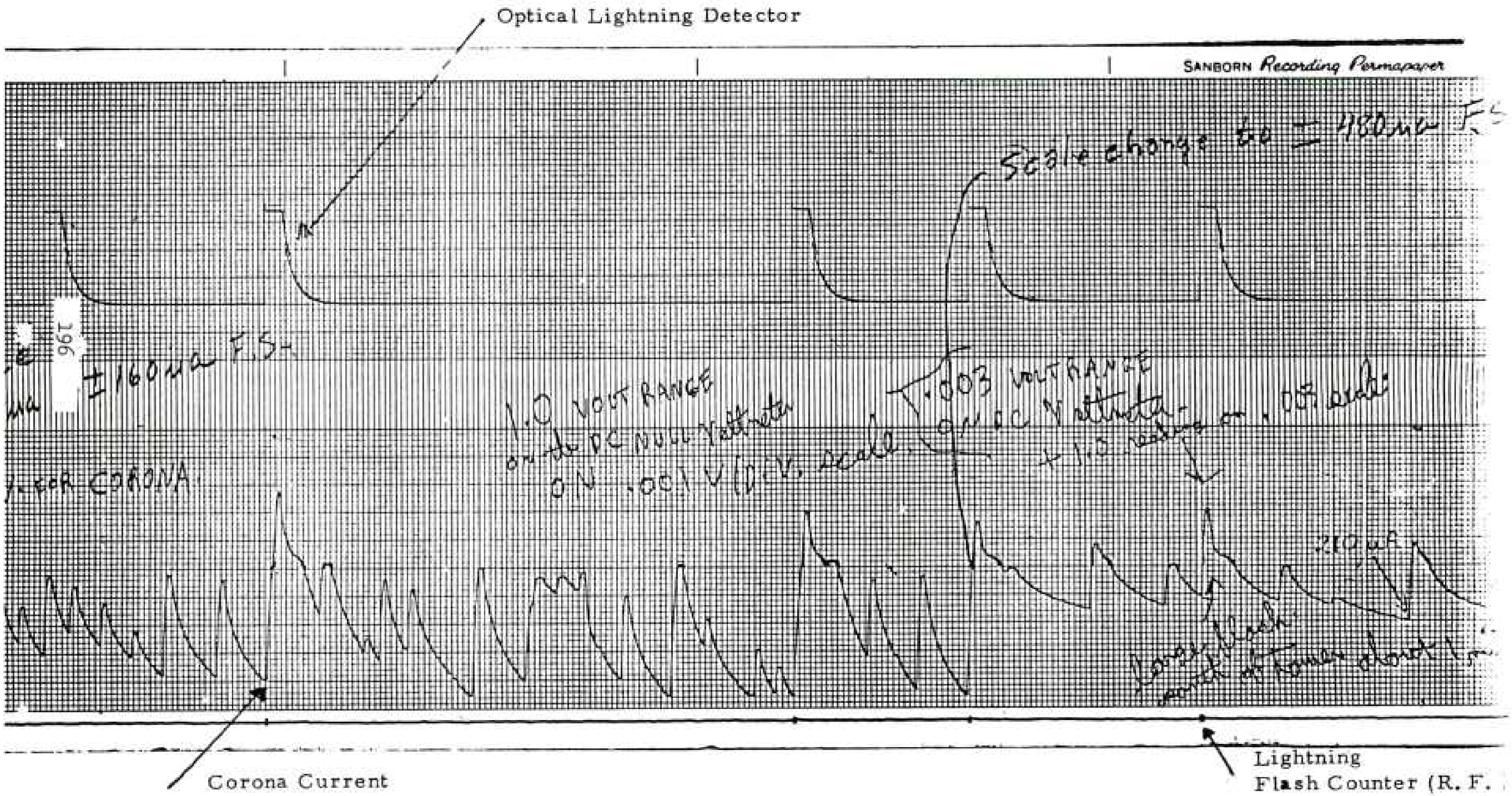


Figure 26. Corona Current Measurements from Single Point at 1200 ft. at C9, Eglin A. F. B.

The conclusions we must once more draw from this data are that the single point emits more corona than the multiple point array and that lightning is still striking the tower, but that it mainly passes harmlessly to ground.

6.5.2 Magnetic Link Measurements

Magnetic link data gave indications of lightning strikes to the tower on five occasions. Three of these were when the array was on top of the tower and two when the lightning rod was on top.

It was pointed out earlier that with the array on the tower there was no possible position of the magnetic links that would give unique current measurements, but they would only give an indication of the strike and a first order estimate of the current. The links at the top of the tower were attached to the array wire and were thus in excess of three feet from the main vertical tower structure. If lightning did strike the array the current would no doubt pass primarily down the 3 outer supports and little would be recorded on the links. At the base of the tower the links were fastened around the array wire and a main structure post and were directed to the outside of the structure.

If lightning were to strike the tower or the guys it would probably pass most of its current to the center of the structure and not down the guy, primarily because of the much lower resistance to ground at the base of the tower.

The first three strikes to the tower in June and July 1975 indicated currents in excess of 19000, 19000 and 37000 A at the base of the tower, but the first two strikes gave no indication of a strike some three feet below the array, whereas the third strike did. This could imply that lightning hit the uppermost guy wires, which pass to the tower some distance below the links, or that the position of the links and the low current was such that the strike was not recorded. Unfortunately the video photographs do not correlate with magnetic link data due to staffing problems and equipment failures.

A strike to the lightning rod in September 1975 passed down the magnetic link arm conductor which showed values in excess of 48000 A, and a second strike to the rod that month indicated values in excess of 25000 A. Like the other three strikes no damage was reported at these times to the tower electronic equipment. This data therefore upholds our suggestions that if the tower ground is intact to the well then no damage will result.

Examination of the array by USAF contractors in September 1975 showed definite evidence of lightning strikes and arcing between the array bolts and the tower.

6.5.3 Video Photography

Supporting the evidence of recorded lightning strikes to the tower that are detected by electronic and magnetic means, there is also the undeniable proof of photographs of such strikes.

Unfortunately during the summer months the video equipment was only turned on for 17 occasions at the forestry tower and 10 occasions at the trailer over a 130 day period when storms were prevelant for over 40 of these days. It has been suggested by Pierce(15 & 16) that there should be over 40 strikes to the tower during the year and so the chances were good that the video tapes would contain photographs of lightning to the tower.

The photographs shown in Figures 27a and b show two strikes to the tower as observed from the forestry tower on 1 May and 8 June 1975. The bright dot in the center of the picture is a fault on the silicon diode tube. Heavy rain was falling at these times, but later in the record the strike point was identified as the tower top. Further photographs of lightning to the 1200 foot tower array taken from the trailer are shown in Figures 28a-c. These occurred in May 1975 within a few seconds of one another and there is no doubt that the strike was to the array at the top of the tower. Two minutes later the tape recorder was damaged by a large surge in the remote control line, which ran from the base of the tower, probably indicating another strike. Figure 28c shows much blooming but indicates an upward going leader as a horizontal branch to the west is shown, whereas two frames later when the camera blooming stops it is evident that the main strike is vertical.

On May 16, 1976, an interesting event occurred on 3 consecutive video frames viewed from the trailer. At the time of a lightning stroke to ground some distance beyond the tower, a spark of maybe 100-200 feet was seen to leave the array. This spark did not meet a downward leader and did not progress to become an upward leader.

These video results show categorically that lightning struck the array a number of times. This data along with the magnetic link data, showed that the tower was struck ten times during our brief recording period, indicating the same strike frequency as Pierce's number of some forty times per year. During all these strikes to the tower no damage to the site electronic equipment resulted because the ground line was intact and had low resistance.

On September 23, 1975, the eye of hurricane Eloise passed close to the 1200 foot tower. The wind strengths were too severe for the structure and the tower blew down, thereby ending all further research at this site.

6.6 Site C74 Eglin Air Force Base

More dissipation arrays were installed at the site C74 sled track during 1972. One of these arrays is a long barrier array running parallel to the track, another is an umbrella array atop an 85 foot tower, and two bed of nails arrays are installed on the top of telegraph poles some 40 feet high to aid in a lightning warning system. The long array consisted of 5 strands of barbed wire suspended about 40 feet in the air on wooden poles and stretching about 1800 feet. During the spring of 1975, while two students from the University of Minnesota were working under this array under heavy clouds that had not produced any close lightning at that time, a stroke came down at a sharp angle and hit the array. On one occasion the same students saw the bed of nails array glowing under storm conditions signifying corona currents in excess of 10 μA. One of the bed of nails arrays was instrumented for

Figure 27 a.

Figure 27 b.

Lightning striking an array on top of the 1200 ft tower as viewed from the forestry tower

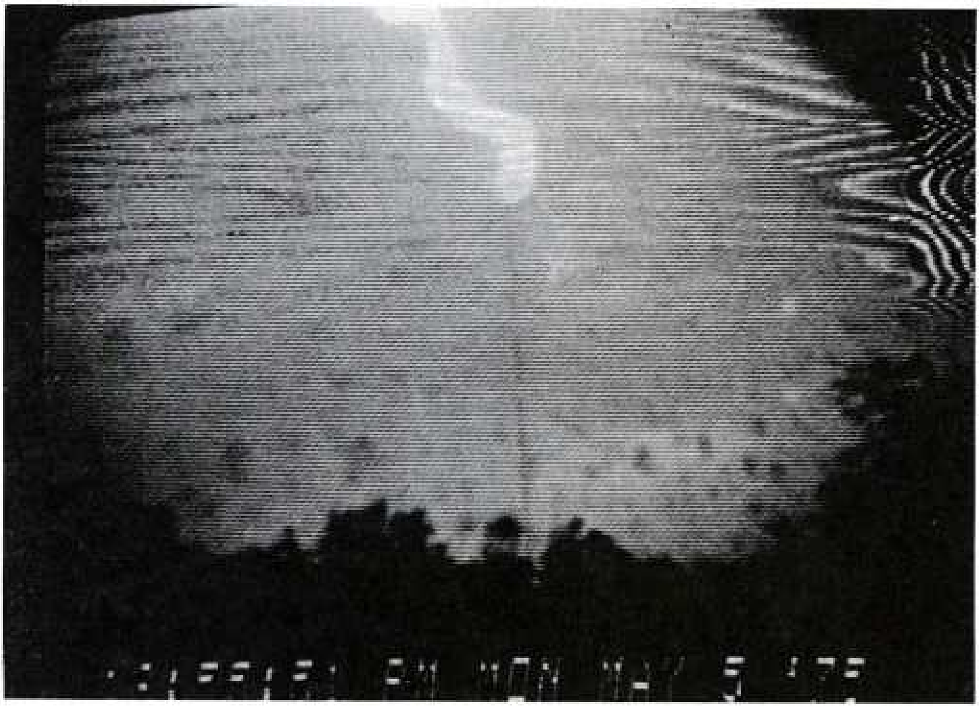


Figure 28 a.

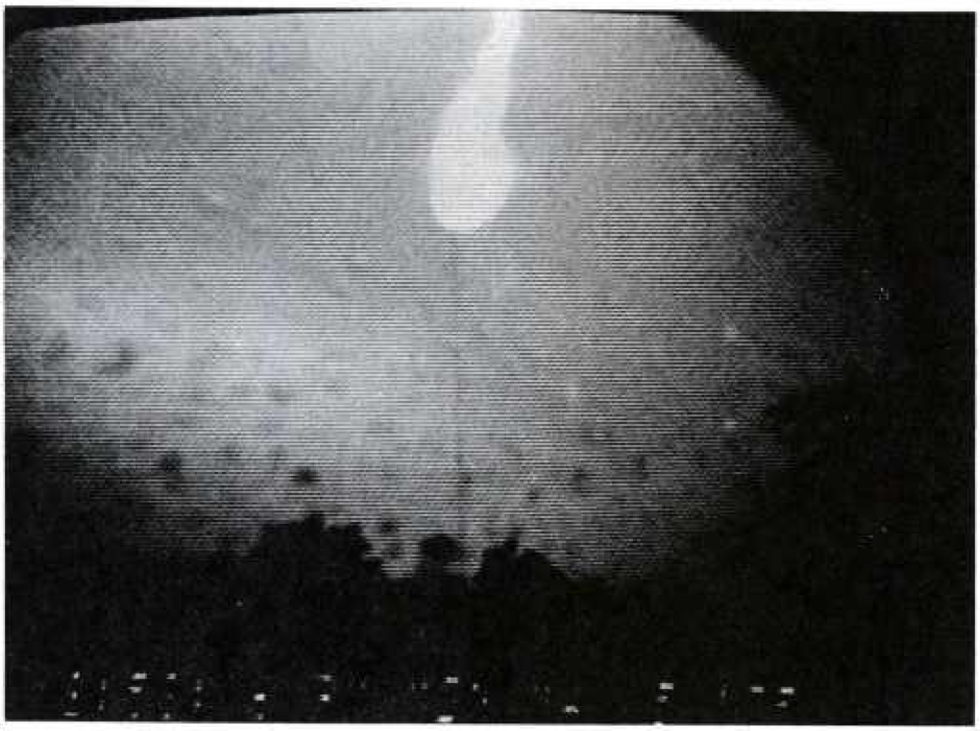


Figure 28 b.
Lightning striking the dissipation array atop the 1200 foot tower twice in two minutes

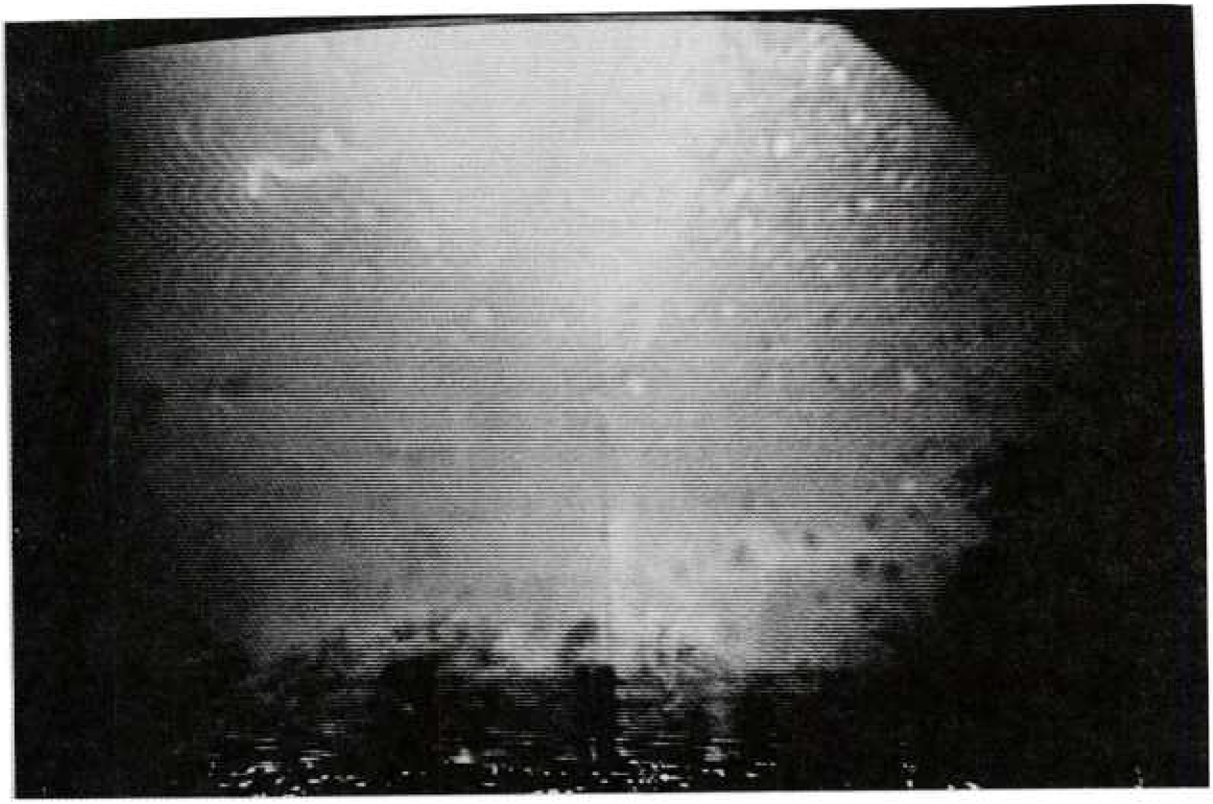


Figure 28 c.

An upward-going leader from the dissipation array atop the 1200 foot tower

corona current measurements in 1973/4 and it was noted that in February 74 the 10 watt 100Ω resistor had burned out probably indicating a lightning strike to the array. This resistor was replaced allowing corona current measurements to be obtained at this site by the USAF and the University of Minnesota for two years.

Atlantic Science Corporation thoroughly investigated this site and concluded without doubt, that Telluric currents were existent, allowing currents of up to 40μA to be recorded when no dissipation was taking place. This current was also of opposite sign to the corona expected under negative fields. In order to confirm these findings the recorded data was correlated with the other bed of nails array which was not used for research purposes. The latter array still had ground currents, but in this case they were only of the order of 1-2μ amps and were of different polarity. These findings make any corona currents recorded from this array redundant and cast considerable doubt on the capability of the device to be used as a lightning warning system in this ground configuration.

7.0 LIGHTNING PROTECTION AT THE NASA ROSMAN SATELLITE TRACKING STATION

NASA operates a satellite tracking station in the mountains of North Carolina close to Rosman. In the summer of 1973 LEA was awarded a contract to design, manufacture, install and test a lightning protection system for this site. The system was to prevent lightning from striking the contiguous facilities of the Rosman STDN station and its far collimation tower; an area of over 180 acres of thickly wooded and mountainous terrain. Prior to installation of the dissipation arrays there was evidence of much lightning damage. Atlantic Science Corporation visited the site in September 1975 in order to examine the lightning protection system and assess the damage improvement that had been reported in reference (20).

A plan of the area is shown in Figure 29 and the various types of arrays are indicated. The site is approximately 1 mile by 0.75 mile and the ground is an extremely poor conductor due to the presence of mica. A photograph of part of the site appears in Figure 30 showing the sort of area the array on the center tower must protect.

The first arrays were installed between the months of July and October 1973 and the initial installation included two panel arrays, two barrier arrays (one 80' and one 100'), 3 umbrella barbed wire arrays (one with barbed wire guys) and two buildings had barbed wire run around the roof perimeter. One further umbrella array was located some five miles distant on a collimation tower. All the arrays were tied into an elaborate site grounding system.

Lightning damage history at Rosman indicates that during 1970 there were 7 days with damage, in 1971 there were 10 days and in 1972 there were 6 days. No damage was reported in 1973, 3 damage days were reported in 1974 and one damage day in 1975. It is worth noting that during 1975, the NASA staff at Rosman only reported 2 days with storm activity classified greater than moderate prior to a severe storm on 27 August 1975 and there were 13 other occasions of mild or moderate activity. A histogram of lightning damage

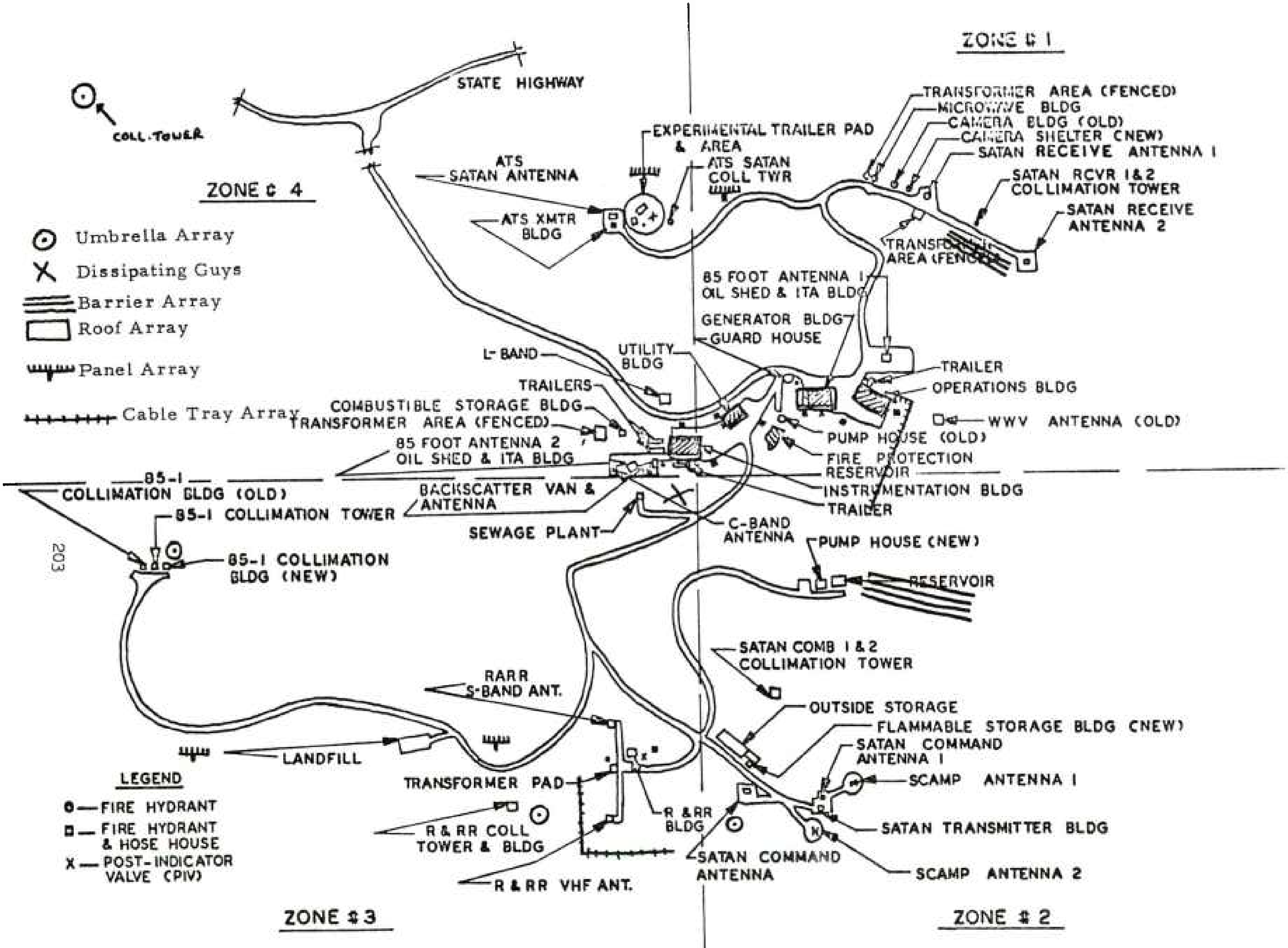


Figure 29. STATION LAYOUT AND INSPECTION ZONES, ROSMAN, N.C.

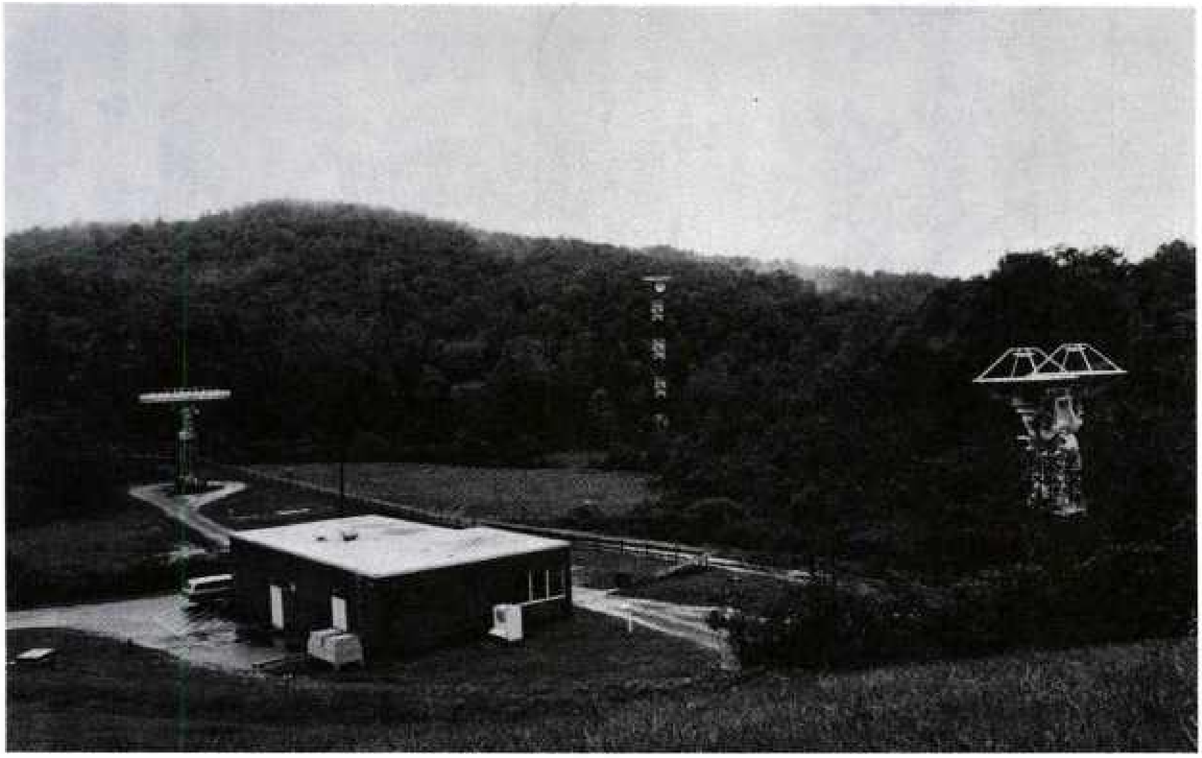
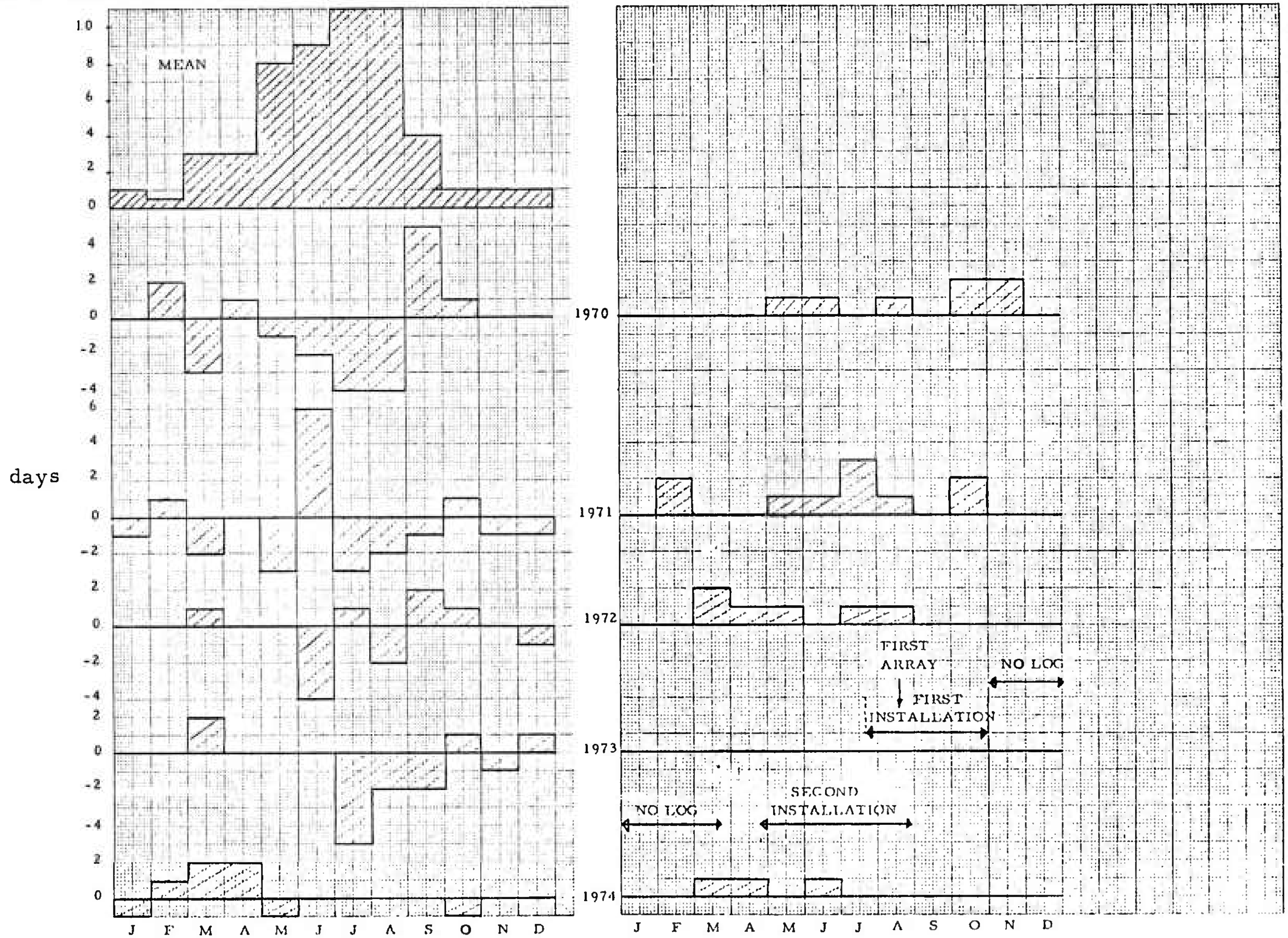


Figure 30.

A small part of the NASA, Rosman tracking site showing a dissipation array on the center tower which is said to eliminate lightning from the area around it



Thunderstorm days per month. Mean value and deviation from mean

Lightning damage days per month

Figure 31.

days per month and the NOAA (National Oceanic and Atmospheric Administration) data for thunderstorm days at nearby Asheville are shown in Figure 31. This figure shows the mean number of thunderstorm days per month taken over many years and the monthly deviation from this mean during 1970-74.

A significant feature is that in 1973 there was no reported damage even though the first dissipation array was not installed until mid-August. In the year 1971, eight of the ten damage days occurred prior to this date, in 1972 all six damage days occurred before the end of August and in 1974 all 3 occurred in this period. Relative freedom of the installation from lightning damage during the year 1973 was due partly to the unusually little lightning activity prior to August, and also to the large number of surge protectors installed during 1972 and 1973 which were protecting the equipment.

Statistically, therefore, one can conclude that as there had been no lightning damage reported in the twelve months prior to the first array installation, that the protection could have been due to powering the equipment down and adding many more surge protectors.

Extracts from log books and telex messages relating to Rosman lightning protection and strikes are illustrated in Appendix 2. From this data is evident that after the first arrays were installed lightning damage occurred in the months of March and April 1974. It is possible that damage also occurred from November 1973 to March 1974, but no logs of such damage were kept. The dissipation array manufacturers returned in mid-1974 and installed two more panel type arrays and also buried a ground wire over the top of a buried cable run from the 85-1 collimation building. This new installation was complete in early August 1974, but in July the log books indicate there was a direct hit to the radar site causing multiple integrated circuit damage. Modifications to the electronic equipment were later carried out at this and other sites to prevent surge damage.

The damage that happened in the storm of March 1974 at the distant tower lead to the installation of diode protectors at that site that were not installed beforehand. There is a possibility that this damage was a result of a power surge. Zener protection was also added to the cables leading into the instrument building after the March 1974 storm. There had been damage several times to these cables with no indication in the log book. The station director indicated that there was a possibility that some lightning damage occurred that was not reported in the book.

A series resistor of some 10-20 watts burned out on one of the barrier arrays in early 1974, indicating a direct strike. This resistor was changed to a 50 watt resistor.

Shortly after installation of these barrier arrays one of them was seen to glow at night indicating corona discharge known as St. Elmo's fire. Golde (reference (3)) indicates that St. Elmo's fire can be seen in darkness at the tips of mules ears or from a raised finger in high mountains. The effect is common in mountainous areas due to the higher electric fields but, as discussed earlier, the presence of St. Elmo's fire does not necessarily indicate large corona currents.

On 27 August 1975 a severe storm hit the area and the damage report in Appendix 2 lists the equipment damage as severe. The report also indicates that there was no evidence of a direct strike to the facility and that the majority of the damage was at the SATAN command antenna site where three coaxial switches were destroyed and there was considerable damage to the circuitry of the SCAMP antenna 1.

A technician reports two flashes in the operators room some thirty seconds apart, but the site director indicates there were probably 4 or 5 separate instances of damage within a 30 minute period. The thunder was being heard in the operations building some 1-2 seconds after the flash, and flashes came every 2-3 seconds. The time to thunder implies that lightning was only 1-2000 feet away and probably on the perimeter of the site. The antenna site was unmanned but students were at the R&RR building a few hundred feet away. One student reports an instantaneous flash and bang from behind him in the direction of the SATAN transmitter. This implies a ground stroke in this region.

Other staff interviewed included an engineer who had lived in the area for 20 years. He had a farm some 10 miles away and thought that during 1973 and 1974 there had been much less lightning activity around both his home and the tracking station. Another engineer said he believed the arrays had reduced the storm activity within about three miles of the site.

After this damage NASA personnel found that the ground wire on the long wire array on the receive hill had a corroded and loose connection, but it was their belief that nominal current would flow. On 24 September 1975 a NASA engineer found a loose wire on the other long wire array. The copper wire came out of the connector when pulled and its previous electrical connection was questionable. It was unlikely however that a large resistance in the line would reduce the corona current significantly.

There have been many estimates of lightning strikes to the Rosman facility. We have seen in Section 4.0 using the equations of Pierce and Price (16) for a region such as Rosman, that on the average there will be about 24 strikes to ground per year. If we assume that ground discharges within 100 feet of an important facility or cable run are likely to cause damage, the strike probability to a danger area would be reduced to less than 5; some damage may however be caused by surges that come in on the power line. Local estimates of lightning strikes have been made by the manufacturers of the dissipation array to be considerably more than this. These estimates were made by examining the number of trees on the facility that had been killed by lightning strikes. This simple approach to estimating strike frequency is not possible on a site that is thickly wooded by over 250,000 trees of which many must die naturally.

8.0 PERFORMANCE OF DISSIPATION ARRAYS INSTALLED AT RADIO STATIONS

To improve the data sampling for examining the efficacy of this particular approach to lightning protection, inquiries have been made with three radio and television stations whose masts are capped by LEA dissipation arrays. Two of these stations are in Orlando, Florida, namely WDBO and WKIS. The third station was KHOF, a UHF television station in San Bernadino, California.

The San Bernadino station, according to the World Meteorological Organization should get approximately 10 thunderstorm days per year which is the value for the mountains of southern California. With such a thunderstorm frequency it is expected that a tower 150 feet tall should be struck 0.14 times per year. The Chief Engineer indicates he believed that damage occurred every winter during the storm seasons prior to the installation of the dissipation array, but most of this damage seemed to be associated with the power system. This may be so, because the transmitter was usually disconnected from the antenna as it operated only 6 hours per day and had breaker points. The arrays were insulated at the top of the tower, but grounded via a down lead that could be used for corona measurements. Surge protectors have been placed in the power line within the last few years and no further damage has been reported. The staff are firmly of the opinion that the array works to some extent, but they indicated they cannot say how effective the protection is. In fact, they state that examination of the arrays does indicate that lightning has struck them at some time.

WDBO in Orlando have two 440 foot antennas insulated from ground. Atop each of these antennas LEA installed three horizontal panels of sharp points each 3' x 4'. The installation took place in July 1975. Previous damage occurred about three or four times per year when the isocoupler, which is at the base of one of the towers, used to be destroyed. Since installation of the arrays no damage has occurred and although the arrays have not been in position long, the engineering staff believe they have prevented damage. An excellent ground mat surrounds each antenna and a 3/16" spark gap enables passage of lightning current to ground. Prior to the array installations there was a 100,000Ω static bleeder resistor between tower and ground, but this was replaced by an RF choke with a very low DC resistance to ground. At 580 kHz the choke has a resistance of some 80,000Ω. It is our belief that the addition of this choke would significantly reduce lightning damage to the isocoupler and could be the main reason why lightning damage has been reduced.

The Chief Engineer of WKIS described his lightning problems. Their three antennas, each some 337 feet tall, are insulated from ground and also have insulated guy wires; a photograph of the arrays is shown in Figure 32. During times of thundery activity the transmitter carrier would kick-off and static activity caused arcing across a 1/4" gap or across the guy wire insulators. This apparently occurred many times during a storm and was not related to direct lightning. It was probably due to a capacitance effect when the field changed by a few thousand volts per meter during nearby lightning discharges. During 12 years of operation they can only recall one direct strike to a tower.

Panel dissipation arrays were installed in July 1975 by clamping two of them directly to each tower top. At a later time the local staff installed RF chokes at the base of each tower giving a low resistance DC path to ground. Since installation of this equipment there has been little change in incidence of lightning or non-lightning electrical damage.

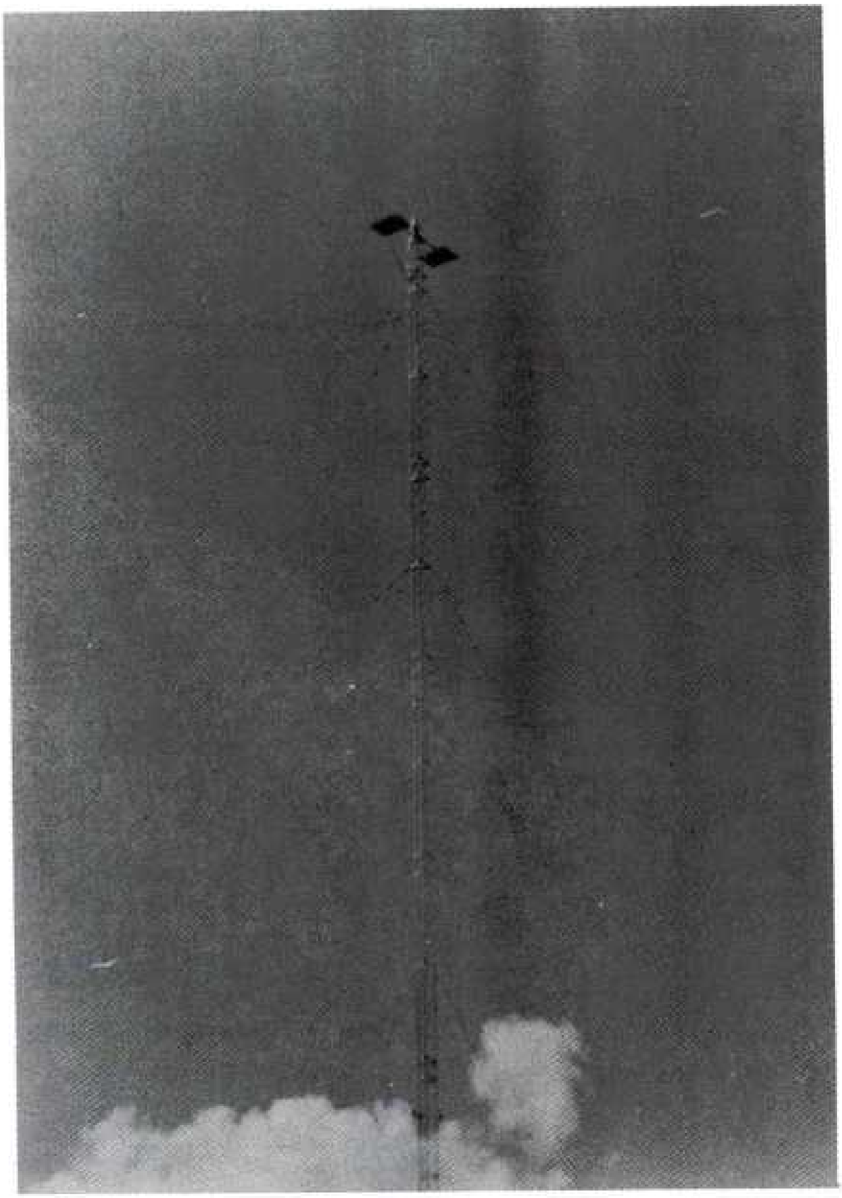


Figure 32 .

An antenna at radio station WKIS Orlando, Florida showing two panel dissipation arrays

9.0 A CRITICAL REVIEW OF EARLIER SUCCESS CLAIMS OF DISSIPATION ARRAYS

The success claims that will be reviewed in this chapter are from the reports referred to in references (12), (18), and (20) that were presented to and accepted by the U. S. Government. These reports describe the early data recorded at the NASA satellite tracking stations at Rosman, N.C. at Merritt Island and at Eglin Air Force Base, Florida.

We believe that much of the corona data presented in these reports is grossly in error. This data consists primarily of corona current measured and recorded from many of the different types of arrays. There have been errors in reducing the data, errors in believing displacement currents are corona currents, and above all, errors in the grounding circuits that give rise to Telluric currents in the circuit. In order to illustrate our findings we will present two instances per site, but there are many more similar unexplained results.

Figure 33 is taken from reference (12) and supposedly shows corona current from the 1200 foot tower dissipation array. The top and bottom trace are both labeled 500 A/division and yet a peak value of 7500μA positive and a peak value of 28,000μA negative are represented by exactly the same deviation Also the displacement currents due to lightning appear to be reversed in time sequence. The slower corona current build up should take place after the discharge and not before it.

Figure 34, also from reference (12) indicates a surprisingly large peak value of 110,000μA even though the markings of .02V/division and 10 ohms would indicate a current of 44,000 A. Once more, time appears to be going the wrong way.

The Rosman data is very puzzling, especially in view of the Station Director's comments shown in Appendix 2, Section C. These comments state that the corona current data is severely degraded by other currents induced in the line as was noted when certain switches were thrown in unrelated lines. Figure 35 shows the recorded corona current (reference (20)) from a panel array at Rosman (this very same figure is also listed as Fig. 8 in the report by Roy Carpenter at the beginning of these proceedings where it is there listed as being from Eglin AFB on May 10, 1974) under a local storm saturating at a very large value of 600μA. As the storm moves away the corona current increases for a surprisingly long period of time and lightning is reported to occur at precisely 45 minute intervals which is obviously interference from a time source.

Figure 36 is a reduction to one graph of corona data (reference (20)) from an array taken over an 8 day period. It is extremely surprising that the corona current remained at a very high value for almost the whole period of time implying a severe overhead storm lasting many days. We infer from this data that there was certainly pick up in the recording lines as the Station Director had suggested and that these results are not a function of corona current.

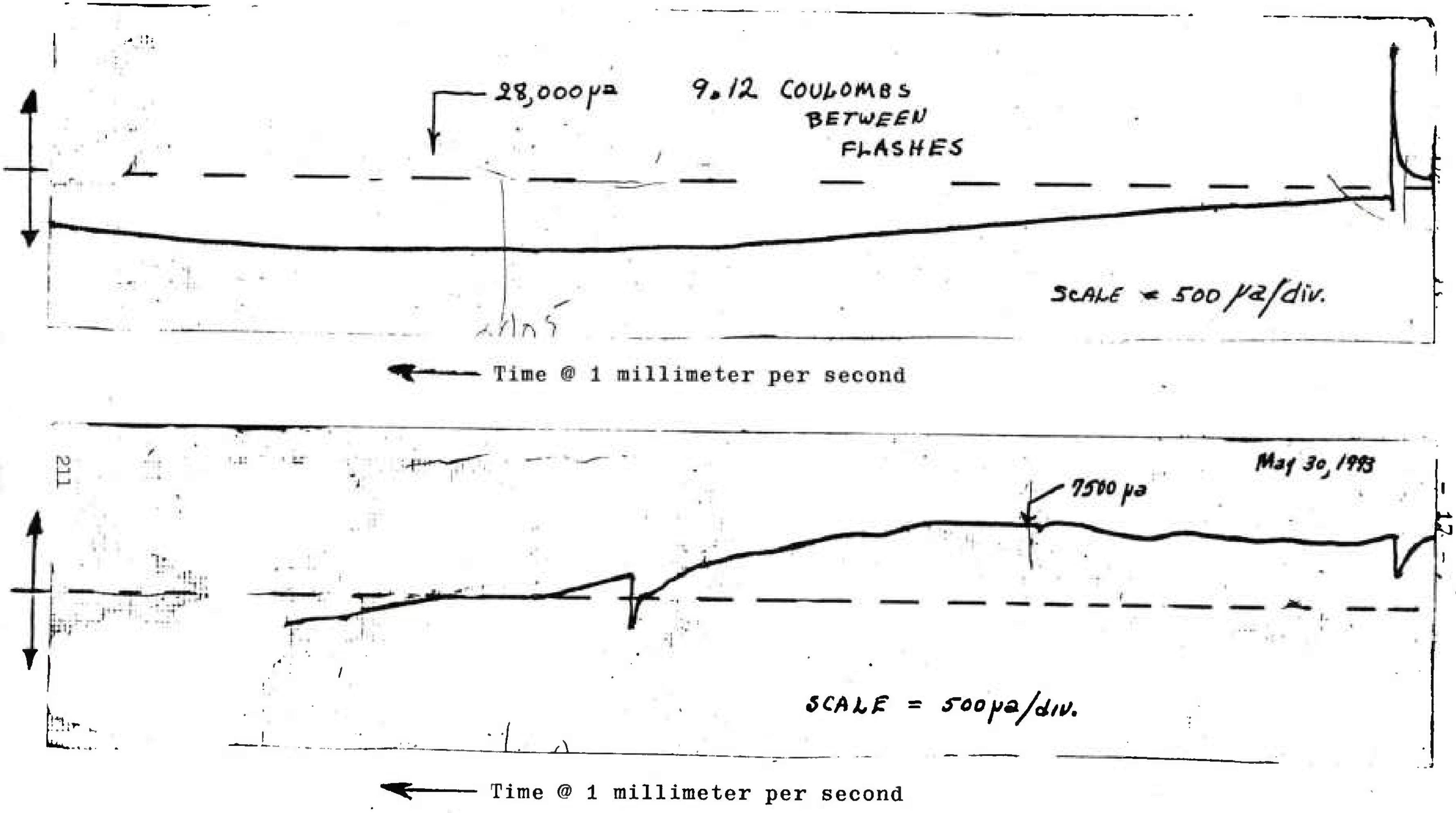


FIGURE 33. ARRAY DISSIPATION CURRENT SEGMENTS, MAY 30, 1973 (as reported in reference 16)

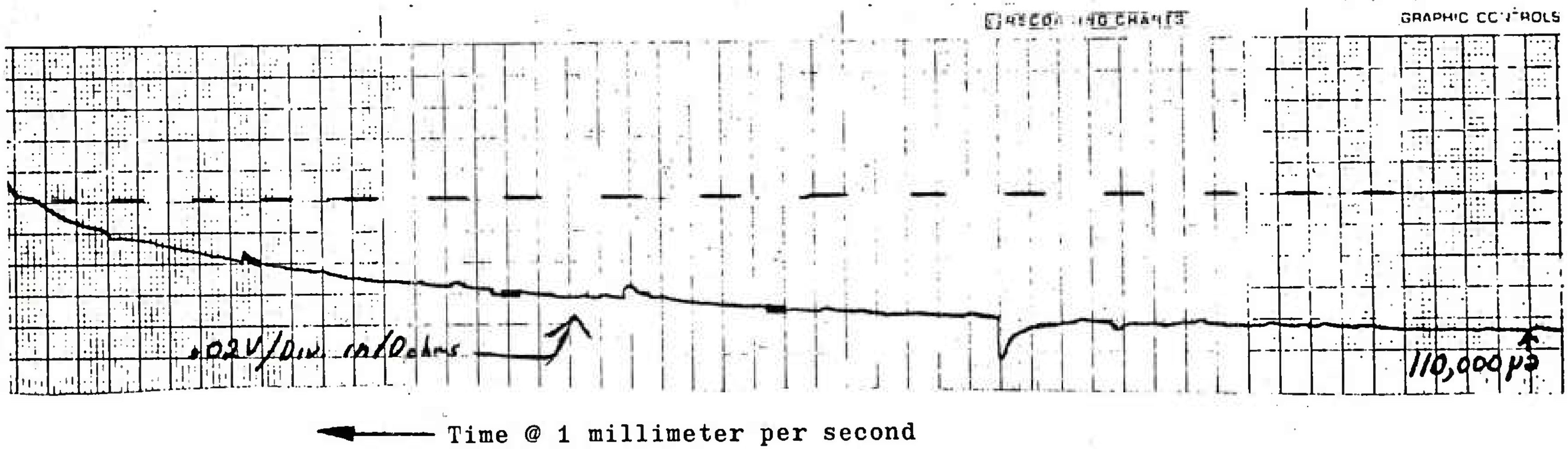


Figure 34. Corona current from 1200 foot tower dissipation array as reported in reference 16

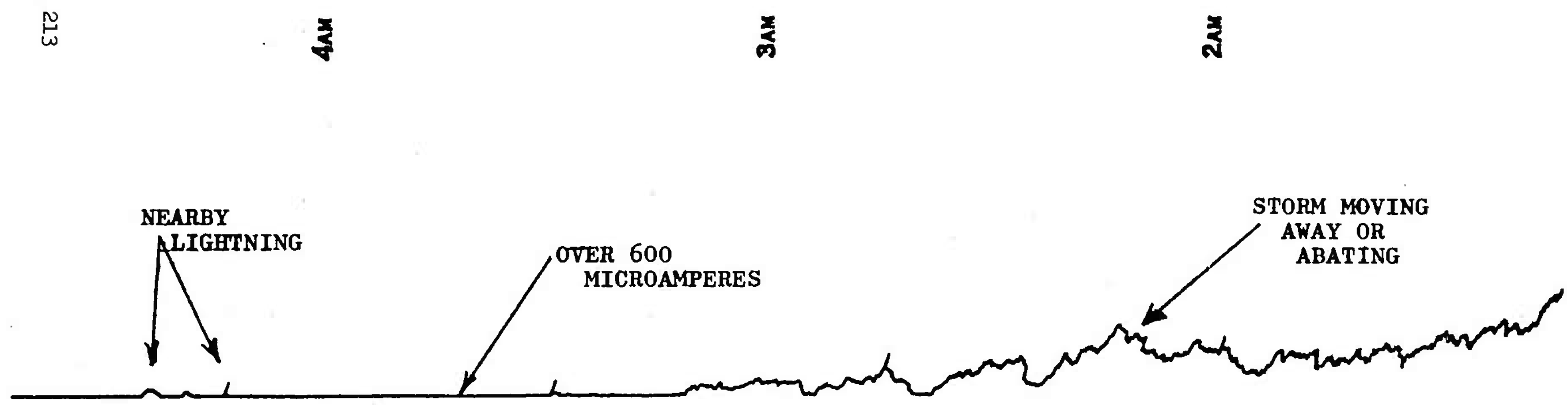


FIGURE 35 . OVERHEAD STORM, PANEL ARRAY CURRENT, MAY 20, 1974
(from reference 20)

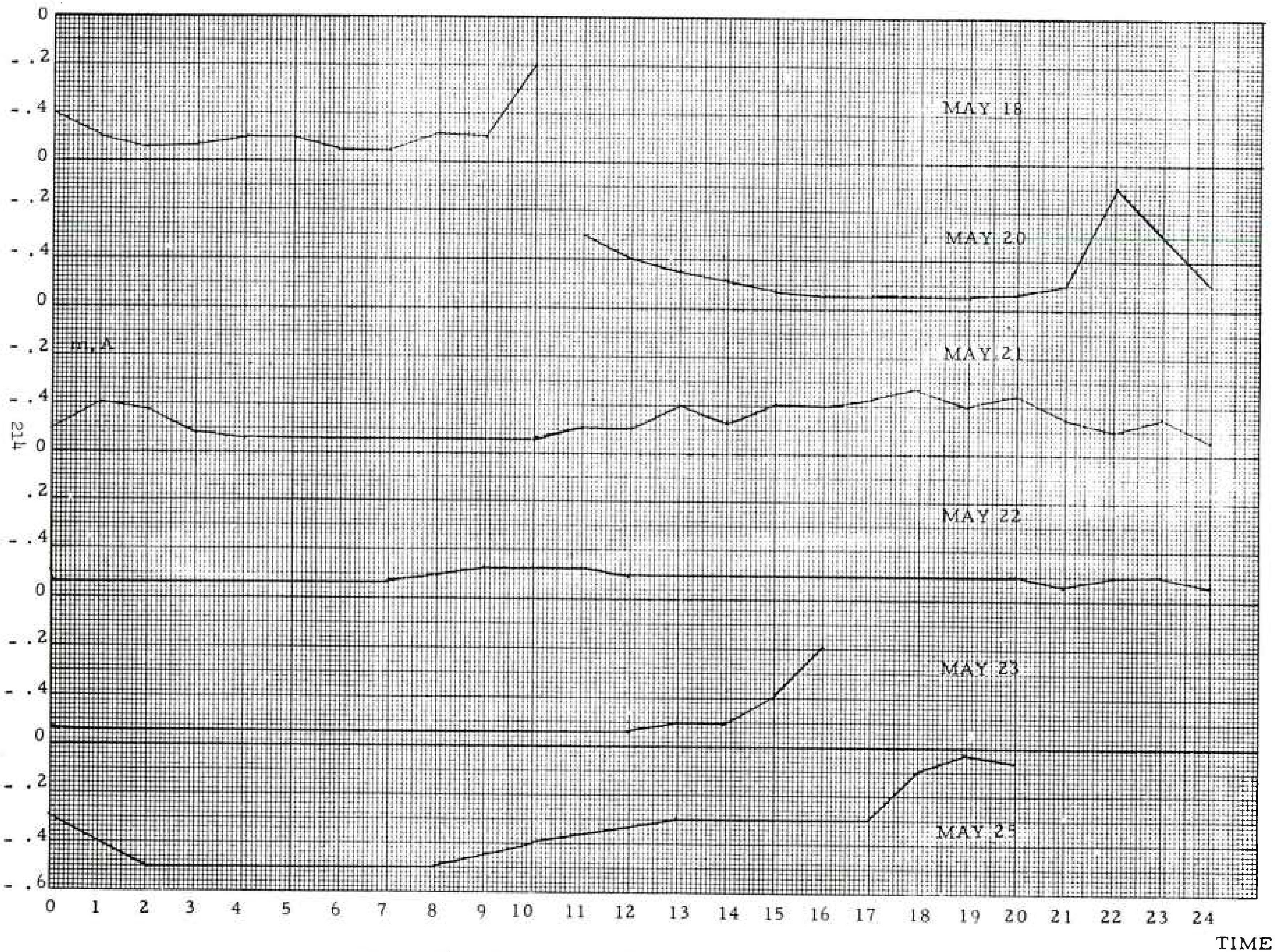


Figure 36 . Rosman panel array corona current from reference 20

Finally, and most surprisingly, a considerable portion of data was analysed from the NASA Merritt Island Launch Acquisition Facility. Atlantic Science Corporation (ASC) obtained many of the original data charts and calibrations that had been analysed earlier by another company and reported in reference (18). In all cases the reduction performed by ASC in no way matched the results in the above reference and the differences were of the order of 10^3. A further feature was that the curves did not bear any similarity in polarity or movement. One such example is shown in Figure 37 where the dotted line is taken from reference (18) and the solid line is ASC's reduction. Our data implies an acceptable value of 22 A from the umbrella array, although the polarity is surprising and may imply line pick up effects. The published data shows a completely different curve some 10^3 times larger. Clearly there has been an earlier gross misunderstanding of the recorded data. The calibration we used in this reduction was taken just prior to the data being recorded.

Figure 38 shows data from reference (18) during a storm on 25 July 1975. The corona current recordings from three different arrays at the same site are strange. Apart from the values being extremely large, the polarities are questionable. The panel array reaches a peak of 2.25 mA, the building array a peak of 67 mA some 1 hour later, and the umbrella array is almost consistently -175 mA except it goes very low when the other arrays peak. It does not seem possible that two arrays a few thousand feet apart can give very high opposite polarity corona current for at least six hours. These results are too inconsistent to admit of an acceptable interpretation.

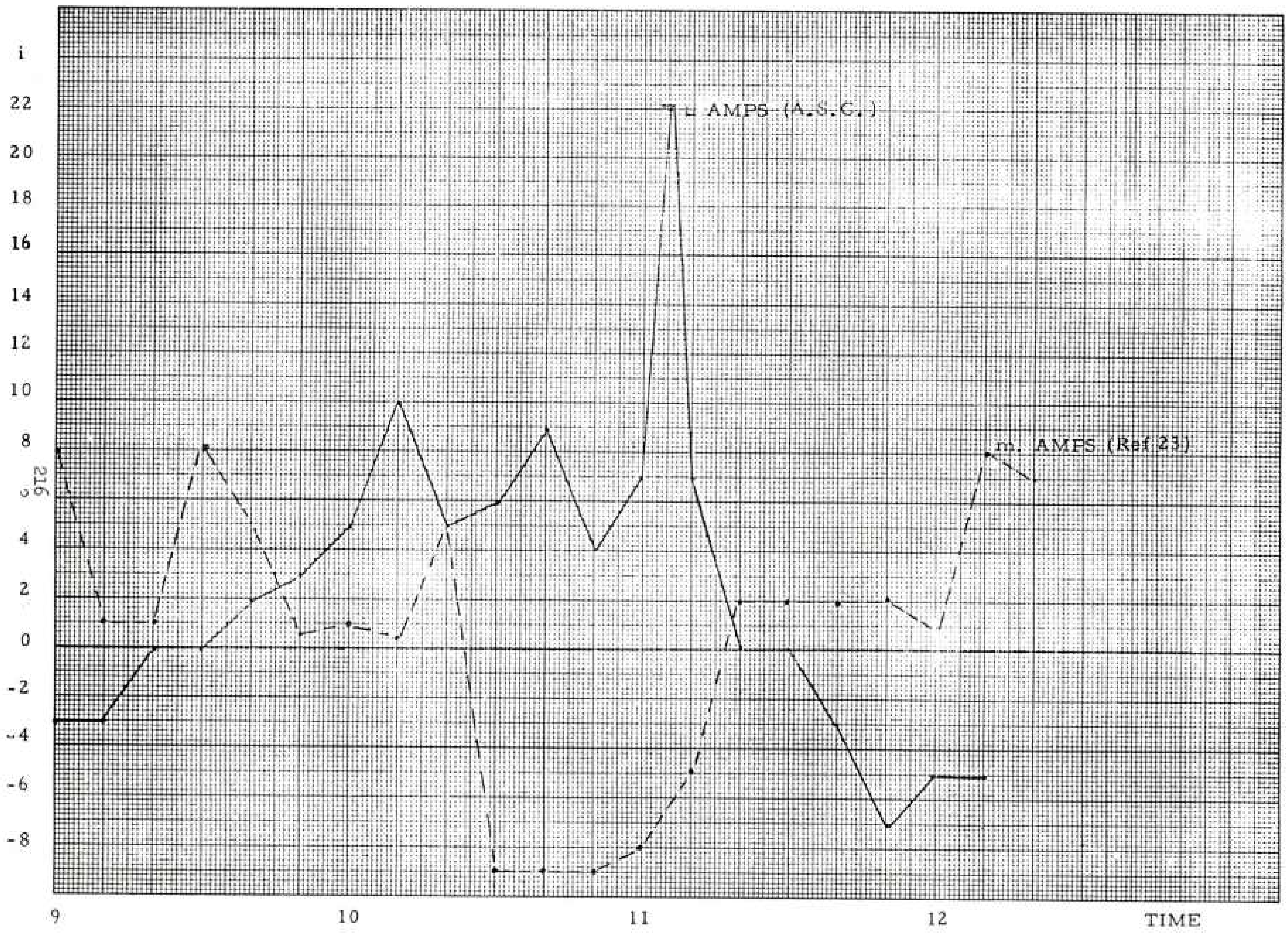
10.0 INVESTIGATIONS AT THE USCG JUPITER LORAN FACILITY

The U. S. Coast Guard Loran C transmitter at Jupiter, Florida uses a 625-foot antenna tower which rests on an insulated base. The tower is connected to ground through the secondary coil of the final transmitter transformer. The ground plane is comprised of many radial wires a few hundred feet long radiating from the tower base.

The base of the tower is shown in Figure 39a from which one can see the insulator, spark gaps and the tower lights' isolation transformer. The antenna lead is seen entering the transmitter building and the return line is seen going to ground.

Magnetic links were placed on the transmitter wire between tower and building in order to measure lightning currents passing to the transformer. Figure 39b shows these links being put in place and also shows the spark gaps across one of the air-cored isolation transformers.

Let us examine the possibility of protecting the tower or the associated electronic equipment against lightning damage. The major problem in this respect is not being able to ground the tower directly because it is being used as an antenna. It has been suggested that dissipation arrays be mounted on the tower which is effectively at DC ground potential and that the ensuing corona current would dissipate the storm. The results and conclusions in the preceding chapters however cast considerable doubt on the feasibility of that approach, which in our opinion, is not worth further consideration.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TIME
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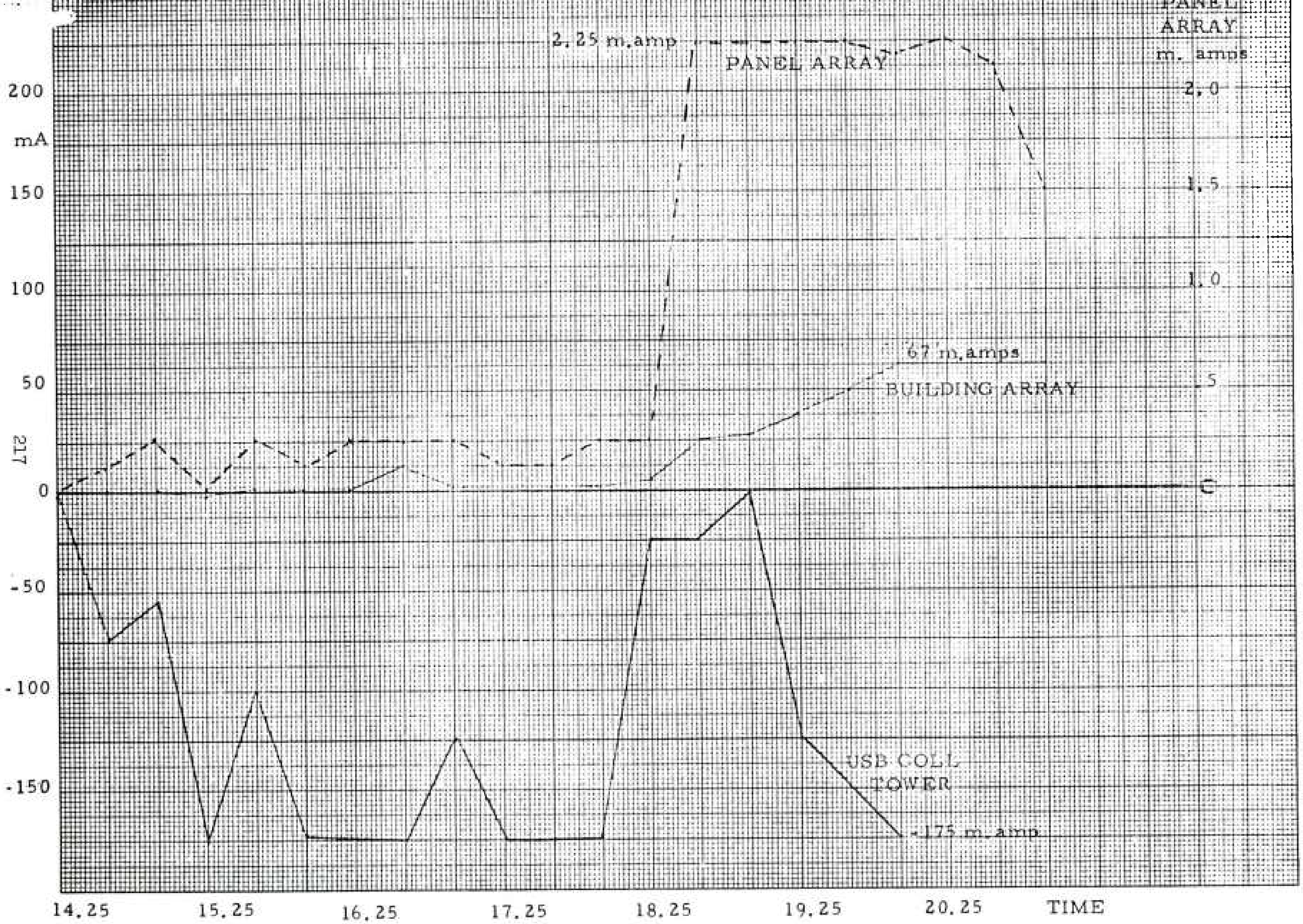

Figure 38. Corona current 25 July 1975 MILA (as reported in reference 18)

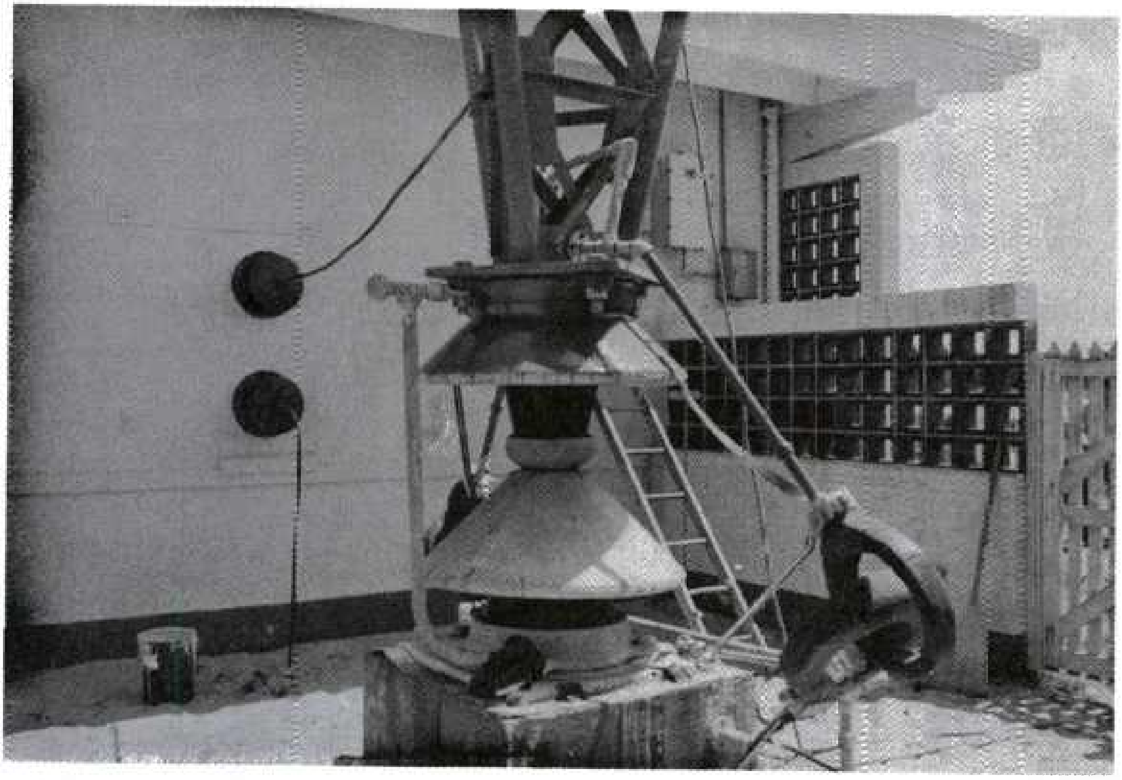

Figure 39 a. The base of the USCG, Loran C antenna at Jupiter, Florida showing the insulated base, spark gaps and transmitter leads

Figure 39 b. Magnetic links being fitted to the transmitter feed cable at the base of the 625 foot Loran C antenna

Basically we must either prevent lightning from striking the tower, or, if it does, we must attempt to protect the transformer from receiving a large portion of the current.

Protecting the tower from lightning strikes is considered by many scientists to be an impossible task, but one or two ideas have been put forward that contain merit.

We have seen in the report by S. K. L. that blunt points tend to go into corona over a larger volume than sharp points and therefore one can assume that blunt points will attract lightning by sending out a longer spark to meet the downward leader. Similarly one may assume that sharp points tend to protect themselves. This latter hypothesis has been put forward by scientists from New Mexico Institute of Mining and Technology. Dr. Golde has also indicated that if uniform corona can possibly be emitted from around a structure then the glow to arc discharge region will possibly be suppressed leading to a reduction in the number of upward streamers.

In practice, however, it will be extremely difficult, if not impossible, to set up the right number of points at the right places such that no singular very high fields exist. If such a configuration can be achieved, it is unlikely to affect the normal downward leaders but may reduce the number of upward going leaders. We have seen in Section 4.0 that for a tower of this height the proportion of triggered to natural lightning is only about 1, implying an average 2 to 3 normal and 2 to 3 triggered strokes to the tower per year. On this basis it was decided to make some simple attempts to investigate the above hypothesis.

Silicon diode video cameras were used at two sites, one to photograph the incidence of lightning to the tower and nearby, and the other to photograph the region at the top of the tower to investigate the behavior of pointed and blunt objects placed at the top. We reported in Section 6.0 that a long spark was seen to leave the array atop the 1200 foot tower during nearby lightning and that the spark did not connect with a downward leader. With a predicted 6 strikes a year to the Loran tower and no doubt a similar number nearby, we believed the chances of seeing sparks were good.

The equipment was installed in late May 1975 and correctly adjusted and aligned by mid-June. Unfortunately the tower was hit by lightning on 18 June 1975 before the video filters had been correctly adjusted for close lightning. The strike caused blooming of the cameras and the resulting photograph is shown in Figure 40a. A typical more distant intra-cloud flash is shown in Figure 40b. No more strikes to the tower occurred during the whole thunderstorm season and after that occasion there were also very few close strikes.

The video signals were degraded due to the strong Loran transmissions but all the data were satisfactory. The electric field change was monitored and during the presence of close lightning an audible tone was recorded along with the video signal. This enabled us to perform a more accurate review of the tower top during such strikes.

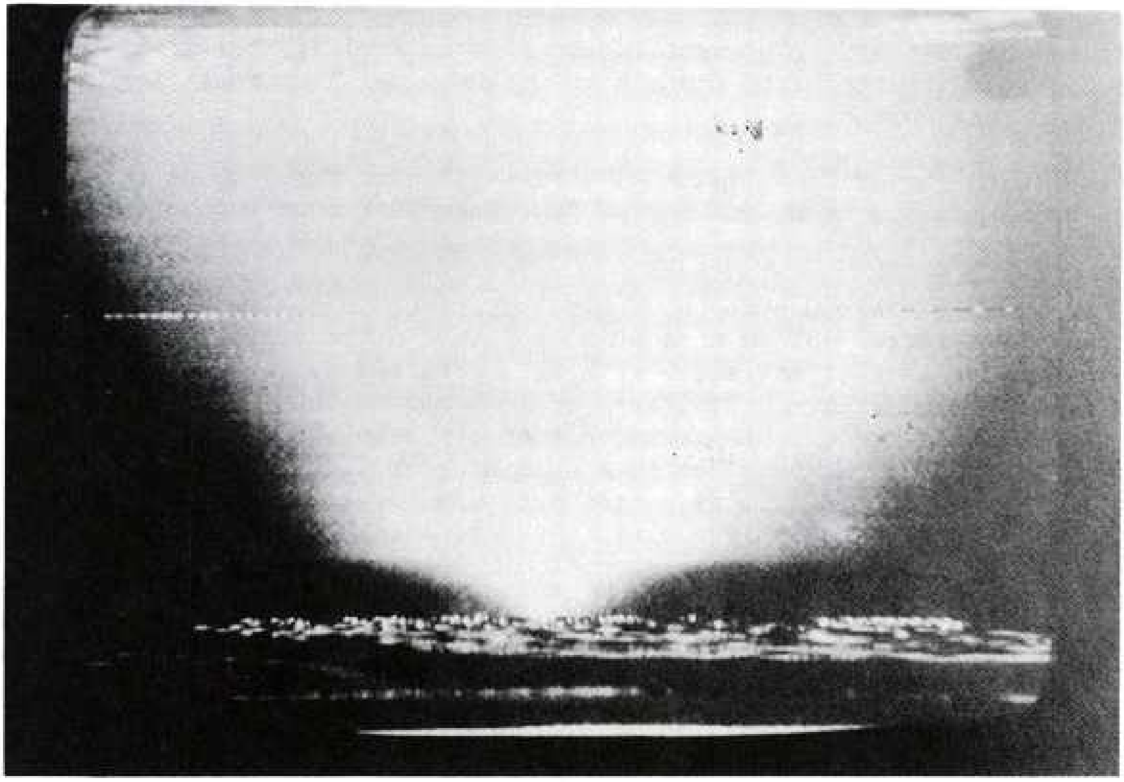

Figure 40 a. A 37kA lightning strike to the 625 foot Loran C antenna causing excessive camera blooming

Figure 40 b. Intra-cloud lightning above the Loran C antenna at Jupiter, Florida

A sharp point and a 12 inch smooth hemisphere were the two objects placed one at a time on top of the tower. Disappointingly for the experiment there were no more very close strikes and so no sparks were monitored. Only one strike to the tower therefore occurred during the summer thunderstorm season.

During the strike of 18 June 1975, 32kA was monitored passing into the secondary coil of the transmitting transformer. This strike contained only one return stroke as monitored on video and was probably upward going.

One may still argue that modification of the tower top with multiple corona points in some hemispherical fashion may reduce the upward going leaders, but we feel it is unlikely that all points could be contained in a "glow" condition thereby eliminating the spark. Downward leaders would also still strike the structure.

Let us now examine what the problems are when lightning hits the tower. The lightning current can be anywhere from a few thousand to a few hundred thousand amperes. This current must pass to ground either by passing directly to ground through the output transformer, or by arcing across the ball gaps, or both. A 2-0 insulated copper wire is installed on the tower and connected at the top and bottom to the main structure. Should this wire be connected to an insulated lightning rod which is struck by lightning, there is a possibility that the current may be "shocked" into passing primarily to the base of the wire which could be connected to a ball gap. Much current will still arc to the tower and pass through the transformer, but the amount may be reduced.

It may appear that we are trying to solve the impossible, but there is really nothing much one can do if no connections can be made to ground for fear of interfering with the transmissions. Maybe if a choke could be made at the Loran frequency of 100 kHz and connected from ground to tower base, a DC path to ground would exist for the lightning current and yet at 100 kHz the resistance to ground would be very high. This is the approach used by AM radio stations, but at those frequencies RF chokes are easily made. The only other approach would be to make sure the ball gaps are kept very clean and smooth and that the gaps are adjusted for minimum distance.

11.0 CONCLUSIONS

This investigation covered the historical, theoretical, experimental aspects and previously published reports relating to the dissipation array principle of lightning protection and elimination. The overwhelming evidence implies that the arrays do no more than a conventional lightning rod would do, and because of their expense and structural size and hazard are not to be recommended. The main findings of the investigation were as follows:

1. History shows that single point corona current exceeds multiple point current.

2. History also shows that currents of a few tens of micro-amperes are the maximum one can expect from arrays atop towers of the order of a hundred feet.

3. Corona discharge from beneath a thunder cell will not influence the cells' electrical charge due to recombination of the corona ions and an excessive time for them to reach the charge centers of the cloud.

4. The maximum current recorded from a large array at 100 feet under a severe storm was under 40 A.

5. A single point at 50 feet always gave more corona than a dissipation array at the same height.

6. Corona current from natural sources such as a few trees will often exceed that of a dissipation array.

7. Corona current cannot provide a protective ion cloud for a large area to prevent lightning already in motion from striking. If such a cloud existed it would be more dangerous than the initial lightning stroke.

8. The dissipation arrays do not eliminate lightning. Lightning has been photographed striking an array many times and the currents measured were of the order of 30-50 kA.

9. Improvement of grounding systems or introduction of RF chokes were the major reason for the success claimed for the dissipation arrays.

10. The reported data and success claims have been critically analyzed and been found to be grossly in error.

APPENDIX 1.

HISTORY OF LIGHTNING DAMAGE AT C-9 1,200-FOOT TOWER

Extracts from Log Books

12 Mar 1968 - Vitro arrived on site. Noticed lightning damage.

27 Jun 1968 - Mr. Hughes finished re-vamping the site water system. All old casing etc. was removed. A new well was drilled about 8 ft east of old well. New pump is 285' deep and is cased to 275', the submerged unit is at approximately 210'.

2 Jul 1968 - Vitro arrived on site. Discovered following lightning damage. Microwave rack circuit breaker was turned off. Dehydrator fuse blown, outside utility outlet on front left corner of trailer shorted out.

12 Jul 1968 - Vitro arrived on site. Severe electrical storm at this time. Lightning is hitting tower several times. Replaced 1 amp fuse in pre-amp panel and returned power back to M/W rack. No other lightning damage noted at this time.

22 Jul 1968 - Vitro personnel arrived on site. Turned on equipment and checked for lightning damage. M/W circuit breaker was kicked and pre-amp fuse blown. No other damage noticed at this time.

26 Aug 1968 - Severe lightning storm in area. Several breaks in public power and local breakers are kicking off.

13 Dec 1968 - Noticed that the 2 bottom beacons on the tower are out. The fuse is blown and on the bottom of the fuse the wire is charred.

30 Dec 1968 - Vitro arrived on site, all equipment on. Found the M/W circuit breaker blown, also a blown fuse in the central panel. Found the front wall power receptical box to be damaged by lightning. The wire outside of the box was burned in two. The dehydrator had a blown fuse due to the lightning damage done to the receptical box on the same power circuit. The electric heater in range shack was damaged by lightning.

14 Jul 1969 - Air-conditioner circuit breaker was open - A/C toward front of van had been in use. Visual inspection showed lightning damage to receptical. Receptical removed and found to be badly charred.

17 Jul 1969 - Measured resistance from power ground to waterline, should read 0 as they were tied together near outhouse last year - read 40 ohms. Dug down and found clamp real loose on water pipe, apparently lightning had burned water line from under clamp. Removed and cleaned clamp and reclamped power ground to waterpipe. Resistance from power ground to water line is now 0 ohms. Elevator would not move. Found fuse Fl in Enclosure 1701 blown - replaced fuse - found indicator for bottom limit SW in Enclosure 1601 damaged by lightning.

18 Jul 1969 - Telemetry antenna and cable from antenna to filter in pre-amp enclosure show extreme lightning damage.

4 Aug 1969 - Crew from Floyd Electric came and repaired water line. It had been badly damaged by lightning at first joint away from where it is tied to tower and commercial power ground.

11 Aug 1969 - Took apart the original TLM antenna for inspection. Found it had practically disintegrated inside from lightning damage.

13 Aug 1969 - There is a severe thunderstorm in the area. All power in van cut from 1415 - 1445. Mr. Evans watched lightning hit top of tower 4 times - may have missed some strikes.

5 Sep 1969 - Mr. Evans disassembled photocell unit, found photocell unit badly burned by lightning - replaced complete photocell, relay and junction block with spare unit on hand.

10 Nov 1969 - There was a severe lightning storm in this area Friday night and have checked all operating equipment in van racks. Found no apparent damage. Wall plug for said air-conditioner shows smoke damage, apparently caused by electrical storm.

26 Feb 1970 - Checked all connections to antennas, etc., said they all

looked good but that the Chu Assoc antenna showed signs of lightning striking it and the base of the new antenna showed signs of lightning damage.

4 Mar 1970 - Noted on way in that third (from bottom) beacon light and SW leg obstruction lights are out - quite severe rain and thunderstorm in area last night. Discovered blown fuse in coax SW power circuit. Replaced fuse 3 times. Fuse will not hold, passed to DCF that we have bad coax SW from last night's storm most likely.

9 Mar 1970 - Vitro tower climbers on site to remove L Band TM antenna coaxial switch. Climbers brought switch down along with new antenna and mounting plate to be inspected concerning lightning damage.

23 Mar 1970 - Found blown fuse in antenna switching circuit. Assume coax SW bad. There was thunderstorm in area last Saturday.

7 Apr 1970 - Tower crew down from tower. Ground plane plate for small telemetry antenna was brought down.and was replaced with a new one, as the old one had been damaged by lightning.

25 May 1970 - Thunderstorm in area. Lightning real close. Took battery charger off charge. Lightning threw rack circuit breaker for RA3C (radios) as Decca was doing Decca monitor checks. I tried to put circuit breakers back into operation - flash of fire then came from breaker. Breaker is shorted - storm still in area. Lightning still striking tower. Found wall mounted dehydrator power indicator lamp blown.

2 Jun 1970 - Shut down equipment because of lightning.

5 Jun 1970 - Power surges kicked A/C circuit breaker.

10 Jun 1970 - Get conduit and wire for new power cable in tower.

11 Jun 1970 - Install lightning arrestors in main power box and in the van circuit breaker box.

16 Jun 1970 - Turned off equipment due to bad weather.

29 Jun 1970 - Damage to coax switch by severe thunderstorm that was in area Saturday night.

31 Jul 1970 - Found blown fuse indicator on control panel lights when power applied to coax SW. This usually means lightning damage has occurred to coax SW at top of tower. Mr. Herring down from tower with coax SW that had been damaged by lightning.

14 Sep 1970 - Found that fuse for coax SW power blows when power applied to SW. This indicates lightning damage to SW.

9 Oct 1970 - Mr. Woods departed for DCF. He took the site TD2903 tape degausser for repair (it had apparently been damaged by lightning).

19 Oct 1970 - Lightning struck tower and burned out fuse in coax switch circuit. Replaced fuse, fuse holds so guess the switch up top did not go out.

22 Feb 1971 - The 230 volt htr in the personnel shack does not work - took it apart and found the thermostat will not close. Must have been damaged by lightning yesterday morning.

21 May 1971 - Mr. Meyers took out the lightning damaged switch and replaced it with one of the old E&M Laks switch which had checked good when it was left up there as spare a couple months ago.

24 May 1971 - We still do not have a water well pump. Motor pulled out Friday because of lightning damage incurred Thursday.

16 Jun 1971 - Found one of the fuses for water pump had exploded during yesterday's thunderstorm - replaced fuse - pump runs - so no other damage apparent.

12 Jul 1971 - Mr. Meyers removed ant. and found it badly burned inside by lightning.

15 Jul 1971 - Lightning damage to coax switches at top of tower.

31 Aug 1971 - We have lost two "talk" power supplies in two weeks from lightning & power surges.

20 Dec 1971 - We are still under heavy rains and lightning has already struck the tower once.

19 Jan 1972 - Found connection from tower & power ground to water well ground knocked out by lightning. Reconnected same. Check from water line under sink to conduit in bathroom reading about 160 ohm, was about 1/4 ohm until recently, went to pumphouse, replaced burned light and checked connection of copper line to well casing. Connection is good. Resistance must be in line coming back to bathroom.

2 Feb 1972 - Ran and buried wire (#12 copper insulated stranded) from water well pump where tower and power ground are clamped (but clamped different place on pump) to power pole where ground takes off from. This gives us positive proof that we are grounded to water well casing. Resistance .3 Ω-Evans.

14 Mar 1972 - Dressed up tower ground wires. Thunderstorm in area, all equipment shut down - Evans.

16 Mar 1972 - Power surge caused recorder to stop, but was re-started immediately. Thunderstorms all over area - Evans.

28 Mar 1972 - 35 -40 mph surface winds from N.W., heavy rain and hail, much thunder and lightning, power surges. No more lightning, turned back all equipment racks, including the M/W - Meyers.

29 Mar 1972 - Turned off equipment during severe area thunderstorm -Evans.

30 Mar 1972 - Cut all equipment, power since thunderstorms predicted -Evans.

8 May 1972 - Severe thunderstorm and tornado warnings, power cut to equipment.

13 June 1972 - Thunderstorms in area - two power failures- 1 second each duration - Evans.

19 Jun 1972 - Hurricane about 100 miles from Panama City. Surface winds 20 mph, much higher up tower. Hurricane predicted to hit coast at noon. Several short power failures and surges, power out on most equipment - Evans.

29 Jun 1972 - Went out on top and checked all equipment for wind and lightning damage - retaped & RTVed several connections - said in general all looked good. Ground strap for the Chu antenna was frayed pretty bad. Severe thunderstorm in area, several direct hits on tower and several run-ins on power line - shut down all but radios after first few surges.

18 Jul 1972 - LEA Carpenter up tower, mounted sensor to top rail and made other connections. Measurements for Carpenter - Evans.

19 Jul 1972 - Love permission to remove lightning rod, Chu antenna, Blade antenna from top of tower per Carpenter requests. Data lines checked from LEA sensors to ground level - Evans.

20 Jul 1972 - Lightning rod and both antennas back up - Carpenter sensors down - Evans.

31 Jul 1972 - Found probable source of cracking heard in van when lightning hits tower or lines near tower. There has been arcing from van to compound fence or vice versa in area of van door.

1 Aug 1972 - Called Carpenter - gave him information - Evans.

15 Aug 1972 - Power outages and surges, bad weather - Evans.

28 Aug 1972- C.O. Payne, Ernie Carpenter begin work of Lightning Eliminator for top of tower, inspections. Payne start assembly of umbrella. Ken Huntley - no authorization for go-ahead, Mr. Love - no written or verbal go - ahead. Love - ok for LEA to start, task # PP RR 68-73 - Evans.

29 Aug 1972 - LEA authorized. Remove lightning rod, Chu & Blade antennas - suspect lightning damage to photocell - Evans.

30 Aug 1972 - LEA prepare for raising of umbrella array on top with

tower maintenance crew - Evans.

31 Aug 1972 - Ernie Carpenter run wire down from top. Roy Carpenter LEA Director on site - Evans.

1 Sept 1972 - Removed Chu and Blade antennas, try to insulate array from tower, looking for short some place along wire - Evans.

5 Sept 1972 - Tried to measure tower and power ground to water well ground loop, but apparently the return wire had been cut outside the compound, even though were shown where the wires were and warned to be careful about them. Ask Carpenter to check it - Evans.

6 Sept 1972 - Untwist wire going to sensor outside of compound for LEA - Evans. Assist Carpenter to insulate antenna from tower - Evans.

7 Sept 1972 - Still LEA checks. Data gathering from LEA left to Huntley and C9 personnel.

8 Sept 1972 - Huntley advised to disconnect array wire at tower bottom and protect personnel shack - Meyers.

13 Sept 1972 - Huntley authorized instrumentation on LEA array, gathering data.

29 Sept 1972 - Tried to read array dissipation, but no indication on micro-ammeter. (Some clouds-not thunder).

30 Sept 1972 - 8:22 - Apparent direct hit on tower. 8:23 or 24 - Second apparent hit on array. Turned tower lights off for test. Stop chart recorder. Mr. Meyers on site to set up outer probe. 10:40 am - Base weather says front here. Virtually no dissipation from array.

2 Oct 1972 - Outside shack light and one obstruction light out. Mr. Huntley on site-took photographs of lightning damage to recorder etc. during Saturday's storm. Elevator would not work. Ground return to main power pole rewired.

4 Oct 1972 - Mr. Evans working on ADTC 9802 housing sensors for array

into new box outside. Found tower light interference is much worse (beacon induction or spark noise) on the recorder since we moved the series resistor out of the shack and to the foot of the tower.
Roy Carpenter called - anxious for a close physical inspection of the array etc. at top of tower.

5 Oct 1972 - Mr. Evans and Mr. Beaman inspect array. No physical signs of damage. Resistance from array to tower (ground line removed) = 350Ω. Resistance from array test wire to tower = 2.5 MΩ.

13 Oct 1972 - Meyers up tower to try and improve insulation of the array from tower. Mr. Meyers on way down tower - had difficulty locating a short from array to ground.

17 Oct 1972 - Mr. Hoffman says the last storm damaged cards in the boxes (amplifier boxes up tower).

7 Nov 1972 - Storm to North. <u>Not much dissipation.</u>

10 Nov 1972 - Recorders on most sensitive scale. <u>No signs of much dissipation.</u>

4 Dec 1972 - <u>Very low dissipation.</u>

6 Dec 1972 - <u>Low dissipation.</u>

20 Dec 1972 - Reverse meter leads to array, different values. This goes higher if antenna leads are disconnected from antenna, so part of leakage is through antenna leads. (Ground currents flowing).

2 Jan 1973 - All N E obstruction lamps, one SO and one beakon lamp out. Several lamps out - antenna switch at top damaged. F6 10 amp fuse blown in tower light box (NE lamps).

8 Mar 1973 - Chu-ass. antenna shorted to array. Fixed it. Also, the Curnie nut that holds the array ground wire to array was loose and corroded. Fixed.

24 May 1973 - 11:30 a.m. Shut down everything because of lightning close by.

4 Jun 1973 - Power supply to bay P6 switched on and arced - smoking-switch shorted and power indicator lamp had blown hole in side of lamp holder. Men arrived to put water faucet on outside of building. No water pressure. Return ground from the pump was burned, so repaired it. No pump power. Points badly burned. Power supply to chart recorder damaged.

18 Jun 1973 - Pump meter burned out - Repaired 19th. Array wire burned out - discovered by William and Peacock, where it comes down.

29 Jun 1973 - Telephone switch on device doesn't work.

2 July 1973 - Pump motor burned up.

17 Aug 1973 - Connected tower ground wire from array to ground at foot of tower.

18 Mar 1974 - Two men on site to discuss lightning damage that occurred about one month ago - H.

20 Mar 1974 - Carpenter up tower to look at array damage and L band antenna damage - H. Carpenter has new type of array he wants us to install - H.

21 Mar 1974 - We started making mounting bracket for new array.

22 Apr 1974 - Range service personnel over on site to remove Hoffman equipment from tower and install test array (LEA).

24 Apr 1974 - Installing LEA array equip. at bottom of tower - Meyers.

21 May 1974 - Meyers up tower to see if we had a hit on the array, because tower light electronic eye was shorted by bad arc, replaced it.

10 Jun 1974 - Found LEA line shorted when trying to remove data -Meyers.

11 Jun 1974 - Meyers up tower to look for short in array line, fixed array short.

Sept 1974 - Prof. Olsan found that over 1 ft of array wire was vaporized on the tower down lead. No evidence of when this occurred.

APPENDIX 2.

EXTRACTS FROM ROSMAN LOG BOOKS AND TELEX MESSAGES RELATING TO LIGHTNING PROTECTION AND DAMAGE

A. March 14, 1972 2111Z

Ref: GSTS 047 10/1829Z March 1972

Subj: Lightning Strikes

The following is a summary for the calendar period from January 1971 thru March 13, 1972.

(1) Lightning Protection Installed:

a) EFC-(TM)-392-311-1. Completed Feb 25, 1971 (Installed in operations and instrumentation buildings).

b) EFC-(TM)-002-672-1. Completed on SR-1, SR-2, and ATS Satan August 1971.

c) Rack Thyrector assemblies installed in 41 racks in instrumentation building racks March 10, 1972.

d) Rack Thyrector assemblies installed in 35 additional racks in operations building during December 1971.

e) Dow NR 7 electrical grounding system - Rosman completed January 19, 1972.

f) April 1971. Checked all installed Thyrectors. Replaced approximately 25 subfloor mounted type that did not meet specifications.

(2) Frequency of Strikes:

Other than for strikes that caused damage to station equipment, no record of strikes on or near the station is recorded.

(3) Extent of Equipment and Other Damage Incurred:

All damage known to have occurred as a result of lightning strikes has been reported as required by OTWL T2/0005Z November 1969 and 16/1621

December 1969. The following itemizes damage during this period:

GROS	061	04/1858Z	Feb 71
GROS	071	25/2818Z	Feb 71
GROS	085	10/2033Z	May 71
GROS	083	11/2107Z	June 71
GROS	059	13/1400Z	July 71
GROS	068	22/2114Z	July 71
GROS	027	27/0525Z	July 71
GROS	076	09/0218Z	Aug 71
GROS	062	20/1930Z	Oct 71
GROS	058	28/2025Z	Oct 71

(4) Downtime Resulting from Strikes:

An intelligent accounting of downtime due to lightning is almost impossible. The complete station has not been down. Times range from a few minutes required for resynchronizing timing cnts to 2 weeks for MMWE rainbuckets.

(5) Ground field resistance measurements are being made quarterly as per paragraph 4.2 and paragraph 3.2 of NCD-(TN) 332-229-1 dated February 10, 1971.

B. March 22, 1974 20.09Z

Ref: Lightning Damage

At approximately 0600Z, March 20, 1974 Rosman experienced a severe electrical storm. The LEA recorder was running, but indicated no DC phenomena. This was probably due to the fact that the recorder sensitivity, as previously discussed, is insufficient. However, large DC spikes were noted, and are assumed to be the results of lightning activity in the area. Charts are being mailed to McKendree.

During the storm damage or failures were sustained on the following equipment:

(1) GRARR VHF transponder (located on near collimation tower) synthesizer failed.

(2) C-Band transponder outage at the Bald Knob tower. Trouble shooting not yet complete.

(3) Solid-state transmitter NBRl. faulted, effecting a Nimbus-5 pass.

(4) Lost near tower collimation antenna control and 1708MHZ source output dropped. If you have any questions contact the COB Eng, Bob Griswold or Bob Davis.

(5) Added 3/25 - Also S band xponder not working - (related to storm?)

C. April 6, 1974 01.46Z

Subj: Progress Report

(1) Lightning Damage

Since the last TTY report from this station, lightning has again damaged the synthesizer associated with the GRARR VHF transponder. No other damage has been noted, despite considerable lightning activity in the surrounding area.

(2) Instrumentation

Records were made of several storms during the previous week. Fluke meters were used as preamplifiers in the array channels, while probes were connected directly to the recorder. While ample gain was available in the array channels, array discharge currents were obscured by currents generated due to station activity. These currents seemed to be associated with antenna activity. Switching Satan receive one from stow to manual had a particularly pronounced and repeated effect.

The magnitude of this problem is such that records produced to date are judged to be severely degraded. In the event that future recordings on the new Sanborn show similar degradation, the array instrumentation lines will probably have to be changed from single wire to twisted pair or coax.

No probe data has been produced to date, except for spikes due to lightning strokes. Low gain is presumed to be the reason for this lack of data.

(3) Change to Coll Towers

The 85-2 optical target mount was changed by LEA from a metal mast to

a wooden mast. In addition, the wiring to the light was removed. Thus the target can now be used only during daylight hours.

Rosman plans to move the MMWE anemometer and rain gauge so that there will be no effect on the GRARR coll tower protective array. This change will be made soon as new mounts for the two instruments can be devised.

(4) RFI Test

Satan receive antenna one was pointed at the MMO Satan array during a thunderstorm to determine if operation of the array caused RFI. No RFI was detected.

D. July 17, 1974 22,27Z

Subj: Equipment Status Report

Ref: 20/1855Z June 1974

ESR update. Modulator Inop. New part on order. Radar hit by lightning causing multiple malfunctions. Replaced following IC's in the processor. 3 ea 7476 IC's, 1 ea N7408 and MC 7473. 1 ea DM 8830 in F5, F17, F41, I45, I44, F7, F8, F19 and G3. Additional IC's remain to be replaced. No more DM8830 IC's in stock. Parts in process of being procured. Modification is in progress to prevent reoccurrence of problem.

E. August 5, 1974 1604Z

Subj: Equipment Status Report

Ref: 20/1855Z June 1974

Ser: MMW 8.75GHZ Radar

Remarks: Modulator inoperative. Replacement modulator received. Installation awaits final checkout of Mod. to prevent lightning damage. IC's wiped out by lightning have been replaced. Op Amp on 01 Reqn. has been received, installed and checked out.

F. August 12, 1974 2030Z

A/D Converter:

While installing the surge protection system for the FETS which failed, it was discovered that more channels will have to be protected. These protectors are being built currently.

G. August 25, 1974 1624Z

Subj: Equipment Status Report

Ref: 20/1848Z June 1974

Ser: MMW 3.8GHZ Radar Remarks: Coax switch operational. Cal. and sync. error corrected. IC's wiped out by lightning. Have been replaced. Mod. to prevent lightning damage installed. Op Amp on 01 Reqn. received, installed and checked out.

H. September 3, 1975 17.22Z

Subj: Lightning Damage

A severe thunderstorm passed over Rosman on August 27 from 1845-2000Z. Extensive equipment damage was sustained at 1905Z, and no new operations were supported for several hours primarily due to total loss of VHF AM command capability. Operations effected were:

SUPIDEN	PST	REMARKS
F1148MS	27/1357Z	CMDS Interrupted
A1329MS	27/1904Z	No CMD
ATS-1,3,5	27/1905- 29/1300	No CMD
A 1036MS	27/2258Z	VHF Only
A 1036MS	23/0039Z	No RTD, S-Band, CMD
A 1036MS	28/0220Z	Deleted
A 1036MS	28/0401Z	Deleted
A 1047MS	28/0444Z	No CMD
A 1010MS	28/0525Z	No CMD
A 1047MS	28/0631Z	85-2 Front End RED
A 1018MS	28/0708Z	85-2 Front End RED
A 1049MS	28/0900Z	85-2 Front End RED

Command capability was restored after 0525Z, but 85-2 front end problems appeared and impacted three additional passes. ATS command capability was restored at 29/1300Z.

The effect on operations was minimized by the scheduled power outage

on the following day, as it was possible to do some trouble shooting while the power was off and while no passes were scheduled.

Damaged equipment identified to date plus failed components (where applicable) were:

1. S/S MMTR number 1, number 2, 3 and 4-PC Board 1A2A4, Q11 and Q 15 defective.

2. S/S XMTR number 1, number 2- and number 3-mode relay assy Q1 and Q2 defective.

3. S/S XMTR number 2-switching and control unit 744-CR7 diode defective.

4. CMD Ant. number 2 polarization relay unit - CR 2, CR3, and CR5 diodes defective.

5. ATS Hughes XMTR select panel - CR16, CR15, CR13, CR10, CR9, CR8, CR3 (IN2071) and bridge rectifier in 28V power supply defective.

6. ATS SCAMP Ant - 2 Demod of Amps defective.

7. Satan CMD Ant number 1 - Numerous defective transistors were replaced in servo cards.

8. Timing to GRARR-Card 3A2 03 and C4 failed. (Main Astrodata Sys.)

9. MSFTP-3 No. 1 - 1 MHZ timing input card AW-1F24U2 failed and was replaced. Serial output clock card A2A1D23U5 failed was was replaced.

10. The WWV receiver in the timing system failed.

11. 85-1 Ant. X-Axis encoder and Yokepot power supply were defective, checkout incomplete. Coll knob tower- 1700 MHZ generator is defective.

12. GRARRS-Band transponder-defective, problem cleared while trouble shooting. GRARRS-Band and VHF antennas -defective syncro amplifiers, repaired by replacing transistors. GRARR pole beacon defective, repaired by replacing capacitor. GRARR timing knocked out of synchronization.

13. ATS backscatter radar - defective, replaced F-12 board (control relay for P/S).

14. Bald Knob coll tower - status unknown, awaiting activation of C-Band system to check-out, 1700 and 2200 equipment O.K.

15. All TTY circuits were red.

16. All SCAMA and FTS circuits were intermittent.

17. SCAMP number 1 inoperative, will not move in either axis.

18. 85-2 136, 1700, 2200 inoperative front ends, cleared while trouble shooting. Numerous electronic systems were knocked out but came up when recycled.

No evidence of any direct hits on equipment has been found to date. A general search of woods in the vicinity of the command antennas continues in an attempt to locate any evidence of strikes. Damage to failed components was generally non-catastrophic - i.e., merely electrically damaged, not blown to pieces. It is likely that induced transients in signal and control cables were responsible for the observed damage.

The lightning protection arrays were checked after the storm and found to be in good repair - except for the Satan receive area arrays, which had questionable grounds. However, no damage was sustained in the vicinity of these arrays.

I. <u>September 17, 1975 22.19Z</u>

Ref: GROS 03/1722Z September 1975

This message is a follow-on to Ref Msg, identifying lightning damage sustained at Rosman on August 27. The following details are now available:

1) SCAMP antenna No. 1 - Transformer T5 damaged (substitute parts used for temporary repair); diodes CR-11 and CR-12 in servo damaged.

2) Intra-site slaving system-protective thyrector damaged, caused slaving nonlinearity.

3) Bald Knob coll tower did not sustain any damage.

4) WWV receiver did not sustain damage. Reported failure was bad potentiometer, first noticed immediately after storm, but not lightning related.

5) 85-1 Yoke power supply-power transformer damaged.

6) 85-1 X Axis encoder has not been diagnosed as yet to avoid impacting DLM schedule.

A search of the wooded area near the command building has not located any evidence of direct hits.

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LIGHTNING PROTECTION OF TALL STRUCTURES

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Lightning Protection of Tall Structures

1 Review of LEA claims

Material published by Lightning Elimination Association of Downey, California, contains several misunderstandings of published information and unsubstantiated claims but little benefit would accrue from discussing these in detail. Two examples may suffice.

Concerning the first aspect, the average electric field strength for which point-discharge (p.d.) currents are supposed to be determined is given as 3 kV/cm for negative flashes and 5 kV/cm for positive flashes (LEA, 1975, p.2). These figures refer undoubtedly to the critical field strengths utilized by the writer (Golde, 1967,* p.461) to calculate the attractive effect of a lightning rod. They apply to an average distance between the tip of a leader channel and the tip of a lightning rod of about 50 m. The correct figures to be used by LEA for the p.d. current should be 2.5 km for the height of the negative charge centre and a pre-discharge field of say 200 V/cm.

As to the second aspect, it is claimed that a p.d. current of 0.2 A was measured on an LEA installation (LEA, 1975, p. 14). The highest p.d. currents ever recorded, to the best of the writer's knowledge, is about 4 m A, viz. 50 times less. This current was measured in one of the 2 television towers on Mount San Salvatore (Berger, 1967, p. 487). These towers are 70 m high and stand on top of an isolated peak, 640 m above Lake Lugano so that their effective height above "ground" can be taken to amount to 710 m (2200 ft)! Although experimental results on the magnitudes of p.d. currents from an array of multiple points are contradictory (Chalmers, 1967, p.248), the writer tends to believe that an array such as that favoured by LEA would be unlikely to produce a higher p.d. current than a single point in the same position. In any case, the short duration of bursts of high p.d. currents and their reversals of polarity (as evidenced in Berger, 1967, Fig. 10, and hundreds of similar records obtained by the writer) are neglected in the arguments put forward by L.E.A.

As shown in Table III of Berger (1967) the highest total charge dissipated by either of the towers on San Salvatore in a full year amounted to - 100 C and + 52 C which is equivalent to the charge associated with no more than about 5 lightning flashes of average intensity. Even so, a fraction only of the ionic current involved in that amount would reach the charge centres in the cloud because of wind action and ion attachment.

* This paper is indeed cited in the LEA report, 1975, p. 10

The writer is convinced that, with present means, point discharge is incapable of discharging a thundercloud and this seems confirmed by the frequency of lightning strikes to forests with its millions of sharp discharge points, an argument which was already advanced by Zeleny in 1934.

2. Lightning protection of tall structures

Lightning strokes of tall structures are initiated either by normal downward leader strokes or by upward leaders from the top of the structure. In order to provide a basis for later arguments the mechanisms by which these two types of stroke are governed must first be described.

2.1 Mechanism of downward stroke

As a negative leader progresses from a charged cloud centre towards a structure a positive point-discharge current flows through the structure into the atmosphere above it. With increasing field strength between the tips of the leader channel and the structure the p.d. current increases until it reaches a fraction of an ampere. At this stage the p.d. current suddenly assumes the regime of an electric arc, due to the phenomenon of glow-to-arc transition (Meek and Craggs, 1953). One or more upward streamers from the structure may thus be formed and these are attracted towards the downward-growing leader. The currents in these upward streamers increase very rapidly into the kilo-ampere range and when contact is established between one of these streamers and the leader the lightning current is believed to reach its crest value.

Photographic evidence for the development of upward streamers and for the meeting between streamer and lightning leader channel is produced in Golde (1967 and 1973).

The foregoing concept has been evaluated quantitatively to calculate the distance, termed the "striking distance", over which a structure is liable to attract a lightning stroke (Golde, 1945). This striking distance is found to be a function of the charge deposited on the leader channel which, in turn, is strongly correlated with the amplitude of the lightning current (Berger et al, 1975). The variation of the striking distance with the lightning current amplitude is illustrated in Fig. 1. It may be mentioned in passing that this curve is close to later curves derived by Wagner (1963) and Love (1973). It should also be noted that the striking distance of a lightning rod also determines the radius of the area around its base which is protected against ground strokes.

One of the assumptions underlying the foregoing estimate of the striking distance is that the length of the last step of the leader is long compared with the height of the structure. This condition applies to structures of usual height but not to tall structures.

Fig. 1 indicates that the striking distance constitutes a probabilistic parameter in the sense that a structure will attract lightning strikes above a certain intensity whereas strikes of low intensity will by-pass the structure and strike the ground in its close proximity. That this is indeed the case has been proven by ample evidence (e.g. Golde, 1945).

For a tall structure, the concept of an attractive distance described above can no longer be applied. It follows that a tall structure can be struck well below its top (see Fig. 20 in Golde, 1973) and strokes to ground in the close proximity of the tall structure must occasionally be expected.

The extreme complexity of the electric-field conditions preceding the occurrence of a strike to a tall structure is shown by the registrations on and near Mount San Salvatore (Berger, 1973). The erratic and, so far inexplicable, pattern of strikes to the 235 m high television tower in Johannesburg (Malan, 1969) examplifies the difficulty in predicting the occurrence of strikes to tall structures.

2.2 Mechanism of upward stroke

An upward-growing leader stroke usually develops only from the tip of a tall structure. The mechanism of its development was first described by McEachron (1941) and later by Berger (1967). It need not be discussed here any further.

A relevant problem is, however, the relative frequency of downward and upward strikes to a tall structure. From observations of strikes to tall structures in the U.S.A., Müller-Hillebrand (1960) deduced that the total frequency of strikes increased roughly with the square of the structure height, as would indeed be expected from theoretical considerations. The relative frequencies of downward and upward discharges, as predicted by Horváth (1971), are plotted in Fig. 2.

3. Tentative suggestion for improved protective system

In ultra-high-voltage testing laboratories it is important to prevent flashover to roof and walls from test transformers and impulse generators. To achieve this object these pieces of equipment are topped with a large specially shaped electrode which assures a nearly perfect uniform field strength over its entire surface. These electrodes, or screens, are produced either in the form of a smooth metal surface or a cage of fine wire. Their purpose is to prevent, or at least greatly to delay, the onset of streamer discharges.

A similar shield could conceivably be utilized on top of a tall tower or mast for the purpose of lightning protection (a simplified form of such a screen is in fact used on tall exhaust pipes of potentially hazardous gas/air mixtures to prevent point discharge and ignition, see Golde,(1973) Fig. 65). If effective, it would prevent, or at least notably reduce, the number of upward discharges from such a

structure and could slightly reduce the number of hits to the top of the structure by a downward discharge. Another alternative might be an array of points, such as in the L.E.A. system, but arranged on a uniform-field electrode. In such an arrangement it might be argued that ideally, no single point would discharge a current of sufficient amplitude to produce glow-to-arc transition and steamers would thus be suppressed.

Apart from its cost, such an arrangement would still be subject to several severe limitations. Thus the uniform field strength over its entire surface could be upset by pockets of space charges floating in the atmosphere. A solid metal surface could be pierced by heavy hail stones and a wire arrangement could be permanently bent by a heavy bird.

Any resulting irregularity would lead to a field distortion and could form the onset point of a streamer.

4. Need for protection

It must be assumed that the present enquiry arises from the need to reduce, or eliminate, the risk of damage to electronic and other equipment installed on and near a tall structure. A lightning strike to such a structure which causes no damage and which is harmlessly discharged to ground can presumably be accepted with equanimity.

The satisfactory operation of tall telecommunication masts all over te world seems to prove that their performance under severe lightning conditions is satisfactory. When, in the writer's experience, damage to equipment has arisen this was occasionally due to omission of well-established principles of protection (Golde, 1973, chapter 8.4). However, much more frequently, equipment damage was due to inadequate bonding within the grounding system of the entire installation complex, or to neglect of electromagnetically or electrostatically induced voltages.

Whn listening to a talk by Mr R.B. Carpenter of LEA at the university of Madison, Wisconsin, in April 1975, the writer formed the strong impression that many of the claims made were due not to the dissipation systems but to improvements in the grounding arrangements of the installations described.

5. Conclusions

In answer to the specific questions raised in Mr. J. Hughes' letter of December 15, 1975, the following conclusions are reached from the foregoing examination:

(a) The claims made by LEA cannot be accepted as substantiated. From present knowledge of the mechanism of the lightning discharge no reason can be advanced to assume that point discharge as produced by the LEA system can suppress the occurrence of a lightning strike to a "protected" structure.

(b) An arrangement is briefly described which might conceivably reduce materially the frequency of lightning strikes to a tall structure but serious questions are raised as to the practicability of such a solution.

(c) It is shown that a structure of ordinary height affords a certain protection to the surrounding area. This protection is a statistical quantity and it is amenable to quantitative assessment. Strokes which are liable to penetrate into this so-called protective area are likely to be of comparatively weak severity. The area protected by a tall structure, while basically subject to the same considerations, cannot on present knowledge be delineated quantitatively.

(d) It is suggested that lightning strikes to a tall structure can be accepted but that attention should be concentrated on the protection of associated equipment. Particular care should be exercised on the design and application of the grounding system.

R.H. Golde

Dec. 31 1975

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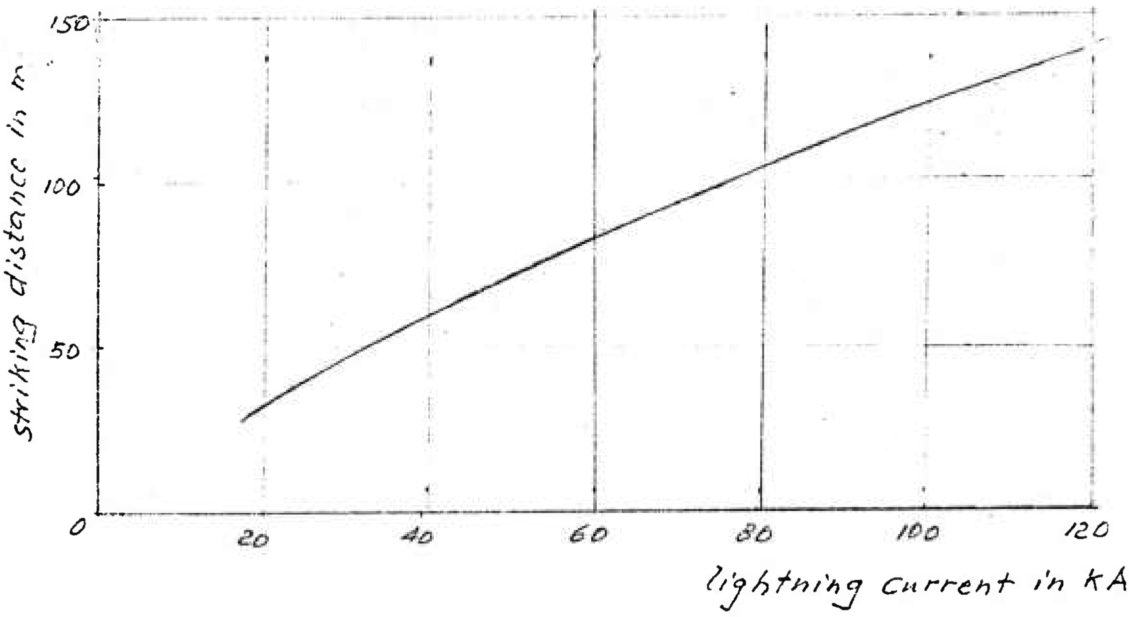

FIG.1 Variation of striking distance of negative strokes with current amplitude, after Golde, 1973.

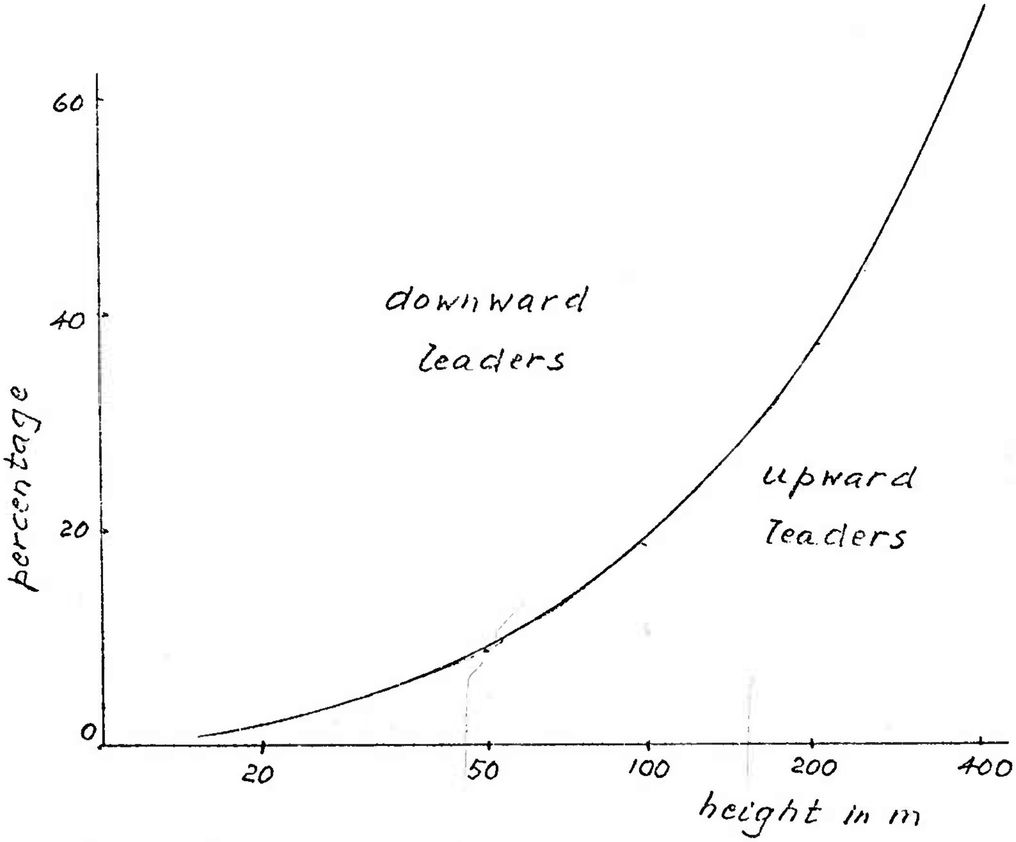

FIG.2 Percentage frequencies of strikes to tall structures iniated by downward and upward leaders, after Horváth, 1971.

LIGHTNING ELIMINATION ASSOCIATES' DISSIPATION ARRAYS

by

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LIGHTNING ELIMINATION ASSOCIATES' DISSIPATION ARRAYS

My views on the currents released by point-discharge or corona from grounded objects under the electric field stresses of overhead thunderclouds correspond closely with the classical theory such as that propounded by the late Professor J. Alan Chalmers. That is, these currents form part of the atmospheric electric circuit of the thundercloud which should be considered as a generator of current and not of voltage.

Consequently, I do not believe that modification of the distribution of this current by the erection of artificial passive discharging points or arrays has any effect on cloud electrification, nor do I believe that the incidence of natural lightning can be reduced in this way.

As far as tall grounded objects are concerned, that is, objects at least 200 metres taller than their surroundings, then I believed that it might be possible that the space charges released by point-discharge current could, in certain circumstances, inhibit the launching of upward leaders or streamers. Thus the possibility of some reduction of lightning incidence to tall structures seemed feasible to me, a reduction perhaps of the order of 20%, but nothing approaching a complete elimination.

In this latter connection, I have written to Lightning Elimination Associates expressing my interest in their claims and my open-mindedness in examining any evidence for the efficacy of their devices in protecting tall structures. No such evidence has been presented to me. I have stated to L.E.A. that I do not believe that their dissipation arrays prevent natural lightning. I have also told them that their sales literature contains claims which probably cannot be substantiated and that therefore they would probably contravene British trades descriptions laws if they should attempt to secure sales by distributing this literature.

I do not wish to be regarded as a supporter of L.E.A. or their dissipation arrays, nor does the Lightning Protection Company. Our decision to contact them was strongly influenced by the numbers of devices L.E.A. had sold to reputable organisations in the U.S., for it seemed unlikely to us that your Government Departments would have bought such a large number of devices if these are as ineffectual as the latest evidence suggests. This suppos$ition appears to have been wrong.

M. F. Stringfellow

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OPEN DISCUSSION ON:

LIGHTNING PROTECTION TECHNOLOGY FOR TALL STRUCTURES

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Roy Carpenter

I'll attempt to be brief. I think what I have to say will be at least constructive, if not helpful to some degree. I am impressed by the last talk (paper by R. Bent) more by the half truth than by the data. Much of the information that was presented I was going to respond to one at a time, but I have decided that that is not the best thing to do. But to give you an example, the array that was used at Disney World to run the test was a reject. We just gave it to them to use for an esthetic evaluation. They were going to use it on the monorail system and so we used rejected material to make the thing up with, so it wouldn't have worked well anyway. I did want to comment on one point about the C-9 site though; I was a little bothered about that I will have to admit. If you read the report you will see that it had been reviewed and approved by the government coming out from C-9, the predecessors of Marlin Forstrom, you will find that all of the "strokes" alluded at that particular time were either in two cases due to the fact that the ground was disconnected accidently. What happened is that we were running data and when we ran data the ground would be connected to the instrumentation, then at night they were supposed to connect it up to the ground again. Well, on two occasions they forgot and those two times it got struck. Many of the others that were identified were created by surges coming in on the line, because if you remember in the discussion of damage, the damage was always in someway connected to the power equipment, like for example the lights or the photocell, that kind of thing. To our knowledge, and I am confident that probably Marlin would back me up, and I am confident that Marlin's forerunner will back us up that it was never struck, they didn't have any damage due to strikes in the tower area for the 22-month period after we got this problem of taking the data and the data equipment resolved. We did have a problem in the way that the data was taken for awhile and we did have a problem with getting the things hooked back together again correctly. They'd rush off to go home and forgot to hook the thing up and for several occasions it caused a problem. Most of the other problems including for example Rosman, have explanations. To our knowledge, and again I take exception, to our knowledge there has been no direct strike to the Rosman facility that was protected. Strikes in two cases were off site. In one particular case where we went back, it was because the cable that ran from a valley up to a collimation tower on the hill wasn't on the drawings that they had given us. We found out that lightning was striking a hill really close to the cable line and so we went back and put a couple of arrays in there and put a ground current collector in to keep the surge currents out of the instrument lines. Subsequent to that, they never had any damage there, including the last very severe storm. In the last severe storm the only recorded strike that we could find was the one on the hill that was mentioned previously, and I mentioned it as well. That strike induced transients in the cables that were running into the cable tray and into some other varied ones all in that same area. So again it was really outside of the scope of

protection and there was no strike to any facility. In all the time period there was no strike to any facility. In all the time period there was no strike to any facility within the complex.

Now, let me ask you a question because I think this is terribly important, in a situation like this what constitutes truth? Think about this for a minute. Here is one of our problems. I think you have seen, from all our discussions, that we don't have any satisfactory theory that everybody is going to agree on. If you look at the data that we have presented, and I can give you names of all our customers, you will find that we have had approximately 10% "failures". However in every case, including one of the ones that Dr. Bent just mentioned, we have either gone back and corrected the problem with one correction, or the correction is about to be performed. At one site that was mentioned we are going to go back and correct the problem. We couldn't go back earlier or it would have been done by now, but they are in what they call their evaluation stage and their coverage is being evaluated. They didn't want it touched until after they had completed evaluation up to 15 November. Now we are going to go back in and we already know what the problem is and we already have a solution and the hardware is already on site.

With reference to the testimonials, we have reviewed the thing that is important and that is statistics. I think we have 178 systems and in only 10% of them have we had a problem. Let me read excerpts of letters from people we have done work for. Here is one from Florida Power Company. "Prior to the installation of the array on our microwave tower we experienced frequent communication equipment failures each year which were attributable to the direct lightning strikes to the tower or near the tower. Since the installation of the LEA array during the fourth quarter of 1973, we have experienced no equipment damage which can be attributed to lightning". He cites now in conjunction with this five equivalent sites. For all of these he gives the incident damage and the module damage and shows that they all had had damage, but this one did not in the subsequent period.

<u>KHOF TV</u> was mentioned, I'll just read a little extra. "A dissipation array designed by Lightning Elimination Array Associates was installed on the antenna in the fall of '71 after two years of repeated lightning strikes at this location and varying degrees of equipment damage and loss of air time. Since the dissipation array has been installed we have had no evidence of any direct strikes."

<u>Keswick Radio</u> was mentioned too. "We have come through our second year without a tower strike and since I was so extremely skeptical about the array in the first place, I thought the least that I could do would be to get off a letter to you telling you that it certainly is doing a good job. We are well satisfied with the installation it has certainly saved us many hours of down time, as well as expense."

K.O.S.I. Denver Colorado. "Thank you for your system. Prior to its installation we had suffered several lightning strikes which caused serious damage plus many other strikes during the year at both our FM station on Lookout Mountain and at the AM station. Since we have used your system we have no problems whatsoever. While I don't know how your system works, I do know that it does work. I can never recall of thanking anyone for selling me anything; however, in this instance thanks."

WSB Atlanta Georgia. "I have been talking with people at other stations around Atlanta. I understand that this has been an especially bad year for storms. We have had no direct strikes. We have had no equipment damage as a result of lightning in the past year. In the previous year we had a couple of strikes that were quite expensive."

CKLW Windsor Ontario Canada. "The effectiveness of this system is readily apparent when the reader compares the lightning strike record of '72 and prior years, 25 outages directly caused by lightning to the '73 experience. There have been no outages directly caused by lightning subsequent to the installation of the dissipation array system. It should be noted that the lightning activity during the two years that the statistics given were comparable. Subsequently, for '74 and '75 he got the same results."

One more thing. I issue all of our customers a warranty. I don't mean to provide showmanship and in a sense I suppose this is, but it's still proof of the pudding. The warranty reads like this:

> "In the event of a stroke to the facility we hereby agree to upgrade that system as required or pay the damages induced by the first stroke at no additional cost to the customer. The extent of this liability is limited to the purchase price of that system and is based on the premise that the array has not been damaged or changed by the customer."

I issue this to all my customers.

Now in going back, as I have in 10% of these cases. Incidentally, in some of these cases I have gone back to it wasn't our fault. For example, we went back and solved one problem for one company who thought they were getting direct strikes in a power line that ran for a long distance in an open area. It turned out he was getting some direct strikes, but his major problem was not that, but induced transients that were high enough because the capacity of their long power line itself was so big that it was a rather large capacitor and it induced enough voltage in that line that it could short out the field of his motors and burn them out.

So what constitutes truth? Now I submit to you that in the light of the fact that we don't have concrete evidence, at least you gentlemen have not established concrete evidence as to how the thing operates, that we have to then rely on experience. That experience has taught us two things, one that we as a company are fallible and that we as a company do not have all the answers and we don't, but we are concerned about doing a job. We can do a job, we have done a job.

It is most unfortunate that the systems that Dr. Bent were given were the ones that we had the problems with and that in all three cases they are the only systems I have of that nature. They are the only ones that were designed that way and they were a cruddy design and I know it sounds like an excuse, and an apology is never any good in a situation like that, but I would suggest that if you have doubts you add up the statistics. Maybe one, maybe two, maybe five, maybe ten is not sufficient statistics but when you get up to 168 I submit that is good evidence. Evidence that it does work and the fact that we have had prejudiced evidence here. Because of that, we attempt to make up for it by our own expense. I forget what my warranty costs were last year, but they amounted to somewhere near $25 to $30,000 in total costs making up for some of these particular problems. Thank you.

J. Hughes

OK Roy why don't you sit down over here and we'll start the discussion. I am sure there will be questions. We've opened this general discussion of lightning protection; it's a problem that has existed I guess as long as we have recorded history. We have a traditional method of protection depending on Franklin's lightning rod. We know that it will protect if installed properly; it will conduct a hazardous lightning strike to ground. We have another system here presented today which intends protection by steering the lightning strike away or by preventing it from striking. We have conflicting opinions about this system. We have the vendor's expression of his belief in his product. We have the evaluation by a government contractor who questions his belief. And now he have one expression of general disgust from Prof. Moore with all of us, and we have some difficult questions before us. We have one question in which the vendor proposes, what is truth? I'd like to leave that question until next year and go to a few simpler questions. Namely to what extent does the LEA array work and how does it work. I am sure some of you have questions from the floor, and some interpretations of your own to contribute. The floor is now open for discussion from anybody.

Bill Durrett, KSC

Ron Wojtasinski and I are flying back into Melbourne, Florida, and there is only one flight that goes into Melbourne, so we will be leaving at 3:30 from here. If there are any questions for Ron or myself on the material that we presented, we will be available until 3:30 p.m.

Dr. Seville Chapman

It seems to be agreed that it is impossible to dissipate a thunderstorm by corona point discharge. This conclusion does not bear on the question, however, of whether it is possible to deflect a lightning stroke from an important structure to a nearby harmless spot. I believe no one knows the answer to that question.

Consider a tower of height h=100 meters in an ambient field under a thundercloud of 100 volts per centimeter or 10,000 volts per meter in a wind of 5 meters per second. Taking 1.5×10^{-4} meters^2/second volt as the mobility of ions, their speed will be 1.5 meters per second in the ambient field. In

this case wind speed is considerably greater than ion speed, so we can neglect the ion speed due to the field.

Corona current is proportional to the first power of point potential and ion speed in either wind or the ambient field. In still air in the laboratory this yields the usual quadratic relationship. Current from a single point would be expected to be (Seville Chapman 1970, Journal of Geophysical Research 75, 2165-2169) about 1.315 x 8.854 x 10^{-12} x 5 x 100 x 10,000 amperes or about 55 microamperes. The radial field from the downwind space charge will be the linear space charge density divided by 2π x 8.854 x 10^{-12} x the radial distance. Space charge blows downwind, and not upwind so that right at the tower the radial field from the space charge is half of what it would be if space charge blew both upwind and downwind.

We reach the interesting conclusion that the field vertically near the tower from the downwind space charge (neglecting mirror images, etc.) will balance the ambient field vertically from the thundercloud at a distance r above the tower of $1.315h/4\pi$ or about 10 meters.

It is interesting that the radial distance is independent of ambient field and wind, and is in fact about 10% of the height of the tower.

It is by no means certain whether the lightning stroke will be deflected by this modest reverse field. Perhaps it may be influenced by even a lesser field, in which case the effective volume of influence may be greater. Conversely we have been talking about ambient field of 100 volts per centimeter, which are often observed at the ground under thunderclouds, whereas as Professor Loeb has shown, lightning propagates in fields more like 2500-4000 volts per centimeter. Thus the modest influence of the downwind space charge from corona may turn out to be negligible. I do not know the answer of whether corona can deflect a stroke (I believe no one does), and I think we ought to find out. The influence will depend as well on whether the charge center in the thundercloud is upwind or downwind of the tower. The effect will be greater downwind. Whether it is significant I cannot say.

There is the question of multiple points.

Unfortunately this subject is more complex than simply: do two points give more or less current than one. The answer depends on circumstances. If the points are far apart and hence independent, obviously two points give twice the current of one. Conversely they may be so close together as in a sense to shield each other and yield less current than one. I have made such measurements. The downstream space charge has a <u>dominating</u> influence on the current from the point. In fact for a reasonably sharp point yielding a few microamperes or more, the downstream space charge <u>determines the magnitude of the current</u>. In strong winds and weak fields the interaction of nearby points is minimal. Conversely in light winds and strong fields, multiple points may yield many times the equilibrium current of one, whereas in strong fields one point may give as much current as many. (For fail safe reasons more than a single point may be useful.) In a small laboratory set up the presence of the nearby other electrode eliminates a lot of space charge that would exist if the other electrode were far away. In such a situation,

multiple points have yeilded more current than one, but to extrapolate this observation to an out-of-doors situation would be completely unjustified. All measurements of current should specify all the geometry in detail, not only near the points but also at the other electrode, as well as wind speed and ambient field, for all of these criteria are relevant. If before a lightning strike current surges in the microsecond domain can be recorded, so much the better.

Most early workers in this field (for example see Chalmers: Atmospheric Electricity, Pergamon Press, 1967) did not appreciate the significance of wind, but there are examples of greater and lesser currents from multiple points. E. T. Pierce has also done work in this field.

Now to some other matters. While lightning itself may not cause much damage to a well-bonded and well-grounded structure, lightning is of course a very transient phenomenon. As Maxwell showed over a century ago, such phenomena radiate. Delicate integrated circuits and even more substantial equipment can be completely ruined by such induced voltages.

Further there is the matter of bonding. Outdoors nuts and bolts often rust or corrode, leading to high resistance, or sometimes to diode effects. Occasionally, grounding cables have bends in them which means undesirable self inductance in the circuit.

As we all know, grounding in sandy soil is difficult. What is needed is a large capacitance, large surface set of well-bonded buried conductors.

Metallic shielding of delicate or operational equipment is desirable to avoid radiation effects.

Good bonding, good shielding, and good grounds are essential for protection, though easy to overlook.

There are also resonances with such things as commercial broadcast station wavelengths, which can have substantial effects. Guy wires may have a shielding function like a Faraday cage. If they have barbs on them they may dissipate some energy from radiation sources that might cause trouble if the whole system is not well bonded and grounded.

In some cases reduction of "outages" (whatever the definition of an outage is) may be due to better grounding rather than to anything else.

I do not care for the term "space charge shielding", though I cannot fault anyone for using it if he wants to. The situation is that the presence of space charge greatly alters the field distribution. The mathematics is always terribly complicated. Space charge is blown around by wind, and moved also by ambient fields. If one does not consider downstream space charge or make approximations for it, then one is virtually wasting his time, since space charge is the primary factor influencing corona current.

The matter of the sharp or blunt point brought up by Professors Moore and Bent goes this way. Capacitance, like volume, or area is strictly a geometrical quantity. A sharp point has a smaller capacitance than a blunt point. Thus the sharp point is sensitive to ambient fields, and to a lesser extent than the blunt point to radiated fields and vice versa. Hence, it is not surprising that the different points may have different relative sensitivities.

I conclude by saying that I think it would be well if we or the government would conduct some fairly rigorous scientific investigations with detailed reporting of near and far geometry, ambient field, wind and current. Such results would be in contrast with some we have seen.

J. Hughes

Thank you. There is an assessment of the difference between a single point array and a multiple point array. Do we have any other comments or questions?

Jack Zill JSC

I have a question for Rodney Bent. I'd like to get one thing clear about the question of how much current we get per point from an array versus a single point. You said that the current in a single point was greater than that from the array. You mean the array current per point?

Dr. Rodney B. Bent

No. The array as a whole. We have no means of measuring the array current per point. We took the whole array, which was a 17 ft. diameter construction of multiple points, and measured the total current from that.

Jack Zill JSC

You say the summation of all the currents in an array of points is less than a single point. There seems to be a lot of disagreement in the literature on that. Llewellyn-Jones has shown that in several cases different scientists under the supposedly same conditions were in disagreement. Scientists, I said.

Dr. Chapman

If we have four points several inches apart with a plate a few inches away we will get more current from four points than from one. The same four points on the top of a tower in a strong field with light wind may give less current from the four than from one.

Roy Carpenter

May I comment on that. I've also done what you have said and I found great differences. Now you can question my credibility as a scientist in this but I've been engineering now for something like thirty plus years and I think I can make a simple current measurement. For example, when we first

evaluated the site C-9 for putting up a dissipation array I made up several different forms of modular arrays just to make an analysis of the kind of current dissipation we could get from that tower. We did something similar to what NASA did on LC-39 and we found current radiations from a single point in the ball-park that has been discussed today up to something of the order of about 1200 microamps from a nine point array.

Dr. Chapman

How far apart were the points, how tall was the tower, and what was . . .

Roy Carpenter

This is a 1200 ft. tower. In this particular case the points and point separation were actually varied on two different modules in order to obtain some correlated data.

Dr. Chapman

Are they inches apart or feet apart?

Roy Carpenter

Well the one that I am talking about now the point separation was on a matrix of about 4" separation. The points were approximately 3 1/2 inches high.

Dr. Chapman

How fast was the wind?

Roy Carpenter

I'm sorry, I can't give you that data. I don't know.

Dr. Chapman

It has a major influence on how much current you will get.

Roy Carpenter

I can see that to be true. But please understand, I am making a comparative analysis under the same circumstances between several different modules so that in the absolute realm it's not good, but in the relative realm it is good. What I am saying is that I got considerably more from the multipoints. One of the things that I have found that I think a lot of us have overlooked here today is that I can see that the single point and the multipoint array in an esthetic environment, where you don't have a relatively active storm in process, could lead to a single point giving more current than an array. I've done this. But first such a design will not do anything, it's just designed to conduct an experiment. An array, however, is designed to do a commercial sort of thing. What happens is that when the storm gets intense and when there is a probability of a strike to that array, then the current through the array surges up very rapidly. I've got recordings that I personally

have taken myself that illustrate this. Some of these incidently, are in the USAF Eglin C-9 report.

Dr. Chapman

I think that data on the ambient field strength that existed, the wind speed, the exact geometry of the points and the tower, and the resulting current would be very interesting. Whoever has to settle these issues should make sure that all those data exist and are part of the analysis.

J. Hughes

Roy, have you published any of those results and put them in a place where they can be referenced?

Roy Carpenter

Yes Sir. The one particular one that I referred to that is I think most valuable in this particular situation, is the report that we published on the activities conducted at C-9. Unfortunately, a lot of the data that was published at the NASA stations, were taken by technicians that had other jobs to do. The data was not well taken at all and it was very difficult to digest and be sure that you had what you thought you had. I know we made some mistakes, but I also question the possibility or the credibility of somebody else taking and analyzing the data because it was that bad. The data that we took at C-9, a lot of it I took myself and I know it is correct.

Dr. Ralph Markson

One thing that Mr. Carpenter said that maybe has been overlooked seemed particularly important to me; this is the directional effect. He referred to this several times. Unfortunately he also referred to ions and so we start considering ions and space charge and everybody seems to agree that it is pretty hard to explain the effects of ions for neutralizing the energy of the clouds with space charge. But what is suggested by the directional effect, if indeed there is any, is some sort of electromagnetic radiation. I am glad that Dr. Chapman alluded to this, and I think one should consider what may be possible through that kind of a mechanism.

Now, clearly what is needed here is some kind of critical experiment. I mean does the thing work or doesn't it, and I would like to suggest that maybe such a test might be possible. Perhaps Kennedy Space Center could be the ideal place, by just disman ling all the pointed arrays that are up there and setting up one good one. If the mechanism depends on the array being grounded or not, this can be controlled. Since there exists at KSC an extensive network of field mills and other instruments to measure storm strength in a qualitative way, a test could be conducted by obtaining sufficient statistics under controlled conditions where the array is connected and then not connected to see if there is an effect on cloud electrification.

Roy Carpenter

Incidently, you mentioned direction. I didn't say anything about that and I should have. We have been able to measure differences of dissipation capability by varying the orientation of dissipators. As you see a storm coming in, if you orient the array directly at the storm such that you are more or less parallel with the lines of equal potential set up by a storm cell coming in, you can maximize your dissipation capability as opposed to having the array look the other way or look straight up, which is incidently why we had the problem at the 100 meter weather tower. We had the problem at C-9 with the second array, because I had failed to take this into account.

Dr. Ralph Markson

Clearly the evidence seems to indicate as you present it, that if there is a directional effect it doesn't have to do with the transport of ions, which are carried almost exclusively by the wind, and it doesn't matter which way the array would be oriented once you create space charge.

Roy Carpenter

I'll give you a piece of history to back that up. I did a broadcast station up in Ohio, and they had six towers. We put the array in and he had a history of something like four outages a year until we put it in and he got clobbered every single time a storm came over. He had some rather bad damage and it was a bit embarrassing to say the least, and he called me up and we went out. I climbed up the top of the tower and I could see right away what was happening. Just the outer fringes were being picked up. I found out after checking with the weather bureau, that the storms were coming in at very low heights. I sent a man out there and reoriented the arrays and the station went through the rest of the summer without a problem.

J. Hughes

Well, let me interrupt here. Charlie Moore wants to make a comment before the people from the Kennedy Space Center leave and that looks like it's within 15 minutes.

Charlie Moore

I have several things to say. Following up what Dr. Chapman has said, it seems to me the important thing here is not an argument about how much charge gets released from a point, the real argument is over what region in space do sustained electric fields exist such that breakdown can propagate. If there is an argument about the amounts of charge that are released by one array or another, we will find that this is a side issue that's not the main point.

I'd like to take advantage of my NASA training and at least draw a conclusion to what I said this morning. I didn't really put the thing properly in focus: a great deal of good work is done at Kennedy Space Center by the people there. I am delighted with the field mill network. I think that the work that

Carl Lennon is doing is excellent and should be supported. My unhappiness is that we are sitting here and that I had to sit through all of Rodney Bent's talk and see Rodney Bent tied up in putting his talents in this sort of effort. In my opinion, people such as Dr. Chapman, Dr. Loeb, Dr. Kasemir, Dr. Freier, the other people here, Dr. Bent, should be worrying about how we should go about answering the questions and designing some critical tests to protect against lightning, rather than worrying about Mr. Carpenter's use of the Franklin phenomenon which clearly works to protect a point. It's very difficult to make a spark jump to a sharp point unless you have a very rapid rate of rise of electric field. (But this effect does not protect other objects in the vicinity.) So in conclusion, I would like to enter a proposal again to the Kennedy Space Center people and any other agencies interested. Let's get some of the people here and sit down and discuss some crucial experiments.

Dr. Heinz Kasemir

I remember we had a talk about this problem at Kennedy Space Center about a year ago. We were not too happy about it but at least some things materialized. First of all, the explanation of it at this time that the cloud does get discharged; I think we agreed already that this could not possibly be done with such an array. Right now the explanation tries to go in kind of space charge screening or shielding, or deflecting or initiating streamers. I think either this is very vague and fussy and has to be looked into, but I don't think there is much hope to it. Now at Kennedy Space Center meeting we came to the second conclusion that there should be some controlled instrument, because we don't have any theoretical explanation. The array may work and nobody may know how, but if it works that really does count. Though I am happy really to see that the Kennedy Space Center people made the first move into this direction, I think the test they ran still leaves much to be desired. Indeed I agree with Charlie Moore that we should get together and set up an instrument, or an experiment which really proves something. But at least the results show there is no really definite proof that the array protects against lightning. I must say I don't know if the array triggers lightning. So, where are we standing now? We sit through another session and again hear a lot of papers. I don't accept any log book data saying damage or no damage, and I don't accept any letter saying from this time on we had no damage. This is not the proof I am looking for. I am looking for recording data which are not biased by people and I think the experiment Charlie is hinting on may be set up in the following simple way. You have to have two towers of the same height. One equipped with an array and the other not, and then record lightning strikes not damage. Damage may depend on grounding and all kinds of other things. So it's very simple, you set up a video camera and figure recording over a year and you see which tower is struck. You may not collect too much data, but at least some data may be collected which are vital and that you can then depend on. Thank you.

J. Hughes

I might suggest just to randomize the experiment, maybe we should put the towers on wheels and interchange them.

Hans Dolezalek

Both Ralph Markson and Heinz Kasemir have spoken of an experiment. Comparing these ideas with what we have seen, I cannot divulge the feelings that we are really in very bad shape with regard to statistics. We do not have, in most cases, any clear indication what had happened before the array was installed. Even if we have it, it's only from one or two years. For this reason, I want to forward to you an offer which Professor Berger has done with whom I have discussed this topic last summer. You know that at the Mt. San Salvatore station there are twenty years of very careful uninterrupted recording of lightning strikes to instrumented towers connected to sophisticated lightning measuring equipment. The station has been closed down because of construction work there; but Dr. Berger is thinking that this type of work could be continued and an array of the type discussed today could be put on one of these towers, or on both, and just left there for a number of years with some recording going on, in order to get better statistics. It was Berger's feeling that such a statistical proof is in the field of lightning really the only lasting proof. Thank you.

J. Hughes

I can't think of a more ideal place than Monte San Salvatore.

Bill Durrett, KSC

So far as KSC is concerned, we would be more than glad to entertain any proposed experiment that would prove this, although I anticipate a little trouble in getting the full agreement of this organization on what would constitute a truly conclusive experiment. The 500' weather tower that we have at KSC has an eleven year lightning history. The first nine years of this history is with magnetic slugs only, and you might make a case that magnetic slugs are not sufficient to establish conclusively that a particular point was actually struck. In the comments we have made here, the only firm proof that a stroke has occurred is camera shots from at least two angles. We don't accept visual reports - or the evidence of an arc which was not there before a supposed strike and was there afterwards. The weather tower is the best place we've got for that. I would like to comment again on what other people have said here twice or three times: there is a great deal of difference between a damage log or an outage log, and a strike log. KSC had no interest in damage, whose actual cause may be questionable. We were investigating whether dissipative arrays would prevent strikes to an object. Our strike logs record hits, whether damage occurred or not. I think it will be difficult to find a place with a long past history of proven strikes, especially if you hold a tight criteria on the proof. It just isn't something which you normally instrument for. The weather tower history may be a little weak before 1974, but it's the place where we would conduct such an experiment if it were done at KSC, and I repeat to Charlie I will be more than glad to listen to any experiment that he proposes.

Dr. Rodney Bent

In answer to Hans Dolezalek's discussions with Professor Berger. Professor Berger did mention this last year at Garmisch also, but indicated even with the considerable number of strikes to the Monte San Salvatore Tower he still thought it would take ten years, if one put an array there, before one really would fully understand whether the array was working or not.

Dr. Ralph Markson

Apropos of talking about experiments, I'd like to comment on the statistical problem that Hans Dolezalek brought up. I think that working at Kennedy Space Center, where you could for one storm repeatedly change the orientation of the antenna, or ground, and unground it. You could develop statistics relatively quickly. You might otherwise have to wait for many years. Looking at the same storm you could run many variations in these parameters and with the electric field and other measurements such as sferics, observe if there is a change in the electrification of the clouds.

Dr. Lothar Ruhnke

I just wanted to comment on the test that Dr. Kasemir proposed using two towers. Probably for cost reasons one cannot use 1500 ft. high towers and if one uses a 300-ft. high tower one might get one strike per year per tower. To get reasonable statistics, let's say 100 strikes, one would have to wait very long and I agree with the ten years mentioned for the case of Monte San Salvatore. Of more importance than going out and making an experiment, or a costly test, is the theoretical aspect and to see if we find theoretical grounds that this system works or might work. Since we do not have that, I think we can just lay the matter to rest and wait until we come up with a good theoretical concept for it.

Dr. Bernard Vonnegut

I think that there are several interesting parallels between the problems that are faced here in modifying natural lightning and those that are faced in modifying natural precipitation by cloud seeding, and I think we've already heard several remarks that bear on this. One of the important lessons I think to be learned from the cloud seeding experiment is the importance not only of physical design, but of statistical design and I think it is of paramount importance to get the statisticians in on this problem before the experiment rather than after the experiment. The question of the design is of great importance. The question of making a design that is realistic statistically in terms of the number of years that you'll have to wait for the amount of money that you will have to spend and it is also important to make sure that you have a valid statistical basis so that there will not be problems that will crop up later. I urge that competent statistical help be brought in early in the game.

Dr. Barreto

First of all Mr. Carpenter, you referred to an evaluation of these arrays. I see them as sitting on the top of a very high tower where the field is high because of the height of the tower. Does it make any difference to have a few points or one point or many points? Has this been evaluated? You only refer to satisfied customers, but I don't see any evaluation of what an array does compared to a single point. I also would like to warn people that what one called here corona pulses are not the same pulses as in Professor Loeb's book. The RC time of the circuit that is used to record them could not possibly do it. These pulses are the effect of many coronas that had happened over the RC time of the recording circuit. They are not positive streamers because these cannot be recorded with your system at all.

Roy Carpenter

As we pointed out, the biggest problem we have in evaluating our system is the instrumentation. I find very little general agreement as to how it should be done, because you are trying to measure something that I find difficult to measure. One of the reasons that we have varied our design considerably is because we've tried. As we have pointed out, we have tried making a laboratory experiment and we have made an elaborate "cloud simulator" and tried to get as large a separation distance as we can to eliminate some of the errors that you get with that kind of thing. Then we have taken our data and put it out in the field and sometimes it agrees and sometimes it doesn't. So we have ended up as I say, going through one of several excursions in terms of our array designs. The way we arrived at our point configuration, the matrix upon which we established these points, the coating that we used which is important, the orientation, the size, all these factors are determined by a comparative analysis, as opposed to an absolute thing, and we try to take this data with field data. Sometimes we get correlation, sometimes we don't.

Dr. Barreto

How many points are in corona in a single array at a given time?

Roy Carpenter

That's a good question. If I quote now for example, several people that were on site at Rosman on at least two different occasions when a storm passed over the area, these observers actually noted that the total array itself went into corona, they could actually see it. This was semi-dusk period.

Dr. Barreto

Was it 60 points in corona?

Roy Carpenter

No not 60 points. This is something in the order of about 2500. You saw one of the array configuration, the whole thing glowed.

Dr. Barreto

In semi-dusk?

Roy Carpenter

In semi-dusk, yes. By this I mean it's toward the evening, it's not totally dark but it's almost. And as the storm came over it blossomed momentarily as the storm passed over and then dropped off, sustained the glow evidently for a minute or so. This happened on two occasions with two different observers.

Dr. M. Brook

I am not going to get drawn into any specific discussion about things I know nothing about. I admit I know nothing about any of this. I would like to caution against the simplistic attitude that you can solve the lightning problem with an experiment, and that you can make a decision with a statistician (or not). I think that you are going to find that like for most things, nature doesn't give up her secrets very easily, and the sooner management realizes this the longer might be the continuity of a profitable research effort, rather than a panic button approach every time something comes up. A small amount of money that might have been invested in this problem over a continuous period of time to learn about the thunderstorm, the lightning, the corona and all of that would have gone much farther than the panic efforts we participate in. One of the statistics that Berger did develop at that beautiful place in Lugano, is that the largest number of lightning flashes, if you put up a lightning counter, occur in the summertime. But the largest number of strokes to the tower occur in the late fall and the winter. In other words, there is a different thunderstorm regime for the two times of year. One is frontal, one is local, and obviously there is a complication here. The lightning machine doesn't seem to work in exactly the same way in those two periods of the year. If you start looking at it carefully in another way you might find three different ways in which this happens. I don't know whether we have the statistics developed in terms of time of year, whether the tower acts to launch an upward going positive streamer most of the time during one of those seasons, or whether it merely emits an upward going streamer to join an initial downward moving negative streamer. This really is part of the problem, and I appreciate that somebody was trying to do it. I think Dr. Bent with the video recording was trying to see whether or not the tower initiates a streamer going upward to the cloud or whether it just responds when the leader, a negative leader, comes close enough to make sparks jump up to meet it. In such a situation, I would imagine that you would have the biggest difference between the action of a sharp point or a blunt point; whether or not you are actually making more lightning strokes to ground by initiating the upward leader.

J. Hughes

Incidentally, in these discussions of design of experiments from statisticians, the chair might point out that even if you are going to involve statisticians to design an experiment, statisticians like a hypothesis to test so there is no way of avoiding the theoretical treatment and the hypothesis raised so that they have something to design around and test with their statistics.

O. E. Smith

You just took the words out of my mouth. The statistician does like to have to draw on the physical scientist some general plan, some domain in which to work in the statistical design of an experiment. I do not have the reports with me, but we have done for Cape Kennedy a number of reports on probability of thunderstorm hits. I will have to admit that the methodology had to be subjective to a large extent because there is really no meteorological record of a thunderstorm hit made in the standard archives of weather. We know only the percentage chance of a thunderstorm occurring at Cape Kennedy. This is defined by an observer hearing thunder and in about 50% of the days in a peak period in the summer the Cape Kennedy observer hears thunder. This is what is recorded. From the individual logs made by the standard weathers proceedings, we develop a negative binomial thunderstorm hit model. Our concern was simply what are the chances of a thunderstorm hitting one of the launch pads at the Cape. We define a thunderstorm hit when we could ascertain that a thunderstorm had come within a five mile radius of a point, or let that point be a launch facility. That probability of a thunderstorm hit is very small compared with the chance of a thundersotrm occurring. I will not give you the number on it, but I think it is around 5% chance. We can look it up in our reports. I would urge you and share with you any plans to use this type of report in designing experiments at the Cape.

J. Hughes

Excuse me. Hank Loos wants to make a comment.

Dr. Hank Loos

I feel that we need a study effort to improve our understanding, in addition to doing experiments. I think this would be money very well spent and I do not feel as pessimistic about the chance of arriving at a good theory as some of the speakers. For instance, it seems quite simple to trace the whereabouts of the ions roughly and recalculate the space charge distribution which results, and recalculate the fields that result, all in a rough fashion that will enable us to distinguish between good and bad configurations. It seems that a man year of theoretical work in this direction would pay off handsomely and give us some guidance.

Dr. Arthur Few

Mr. Chairman I would like to propose that we redirect the discussion back to the central issue. I think that we have seen evidence here today that the array does not eliminate lightning. We have seen pictures of lightning striking the array; thus, I think that we can simply say that this array does not eliminate lightning. If the array acts in some way to alter or to decrease the amount of lightning strikes, and if the effect is associated with the ions, then I think the experiments have already been performed that show that a single point could do as good or better job than an array could do. Hence, I don't think we need to repeat that experiment again. I think the only experiments that need to be done are the ones that are currently being done by

Charles Moore. I think he is on the right path; he is trying to understand the physics of what's going on. I think we just have to give him a little bit more time to collect additional data, but I think that is the right track.

Furthermore, I don't think you will ever prove anything with a statistical experiment. I think we have to understand the physics of what is going on.

As far as the evidence on the protection by the arrays, I have seen nothing that pertains to this array that it makes me believe that it gives anymore protection than any other good lightning protection system.

Roy Carpenter

I take exception to your comment. I do not believe that you have seen any evidence whatsoever that it proves that it does not work. What you have seen is that we have made mistakes, which I have already concurred to be true. We have again, and statistics are difficult things to play with, recognize the premise that statisticians can make numbers lie, and I think that we have seen a lot of that. I am attempting to avoid that because this is my livelihood. As I pointed out, we have 178 systems and we had 11, I think, that we said we went back to and repaired and reworked. We have had no failures that we have not been able to rework that I have been told about. Now, the problem faced and the data upon which you have based this premise, are on the work that Dr. Bent has done, and I am not saying anything negative about his work, the problem was he had the wrong things to work with and it is not his fault, it is mine. But nevertheless it is true. I can, in private session, sit down and point out why they didn't work. I know why they didn't work well. Understand this, with our system I found this to be true, that when it doesn't work well it doesn't work entirely. Very often it will actually attract lightning. I sighted for example, the situation in one particular set of towers where we actually increased the strike ratio in a period of several weeks from maybe six a year to about six a week, or more. And then after having gone back and made the changes they again had many storms, according to the station director, and they had no problems. Now, the reason that we had that problem is the same reason that we are having the problem at the NASA meteorology tower and at the C-9 site. It was an unfortunate oversight on our part. Now you say you can't base your statistics on damage reports, well that is true but that's not negative it's positive, because what a damage report tells you is that you had a strike and you had damage. What it doesn't tell you is the number of strikes you had. If you will evaluate the statistics, such as for example on a broadcast station you'll find that everytime they have a strike where there is damage you had ten or more strikes where lightning just tripped the transmitter off and went back on the air again. So, if we say we have 25 damage days per year that means that they probably had 100 strikes that year, or even more. Now, they know when they have a strike; you can talk to the engineers on side and they know whether they get strikes or not, the transmitter trips off and when they examine the ball gaps they are burned. So, although this is not good data that we can sink our teeth in, it gives us a good indication of what is going on. So, again I take exception to the premise that it doesn't work. I concur that the design is critical and that you can make mistakes.

Dr. Arthur Few

As I recall, Mr. Carpenter, 18 months ago at the meeting in Cape Kennedy you were using the Eglin Tower, site C-9, as the example of a success case. Here at this meeting (now that we have had an objective view of the performance of the tower) this is considered an exceptional case which you say we cannot use as good evidence. It is my contention that if we would look at every single installation that you have with the same objectivity and in the same detailed manner, which Rodney Bent has applied to the four that he has examined, we would find the same thing and you would end up having to explain special considerations for each of the installations.

Roy Carpenter

Well, be my guest, but first understand this, and again to reiterate, going back to C-9, the first 22 months to my knowledge and to the knowledge of both the people who were on the sites and the project engineer responsible for that thing, they had no strikes, except for the two cases where they forgot to put the ground in. They may have forgotten to ground at other times, but we know they forgot the ground those two times because they admitted it themselves. The other damage again that they had, came in either on the telephone line or on the power line. Now, that is what half truths do for you. You are going to have to go back and look. You can look at the log, which tells you the damage, but it doesn't tell you what the conclusions were. The conclusions come some time after when they go back and look at it. The problem was we changed the array and I thought I was improving it and I goofed.

Dr. George Freier

I would like to ask a question about people's concept of ground at these stations. At the C-9 tower I heard the statement that the well served as ground. I believe that this well had five tenths of an ohm to ground and I can't conceive of getting a much better ground than the well; and, if the well isn't ground, what is ground at one of these stations? I have seen a lot of anomalous data which without proper grounding considerations really adds up to non-physical causes, and I am sure I can explain every bit of it in terms of bad ground connections and the behavior of the tower and the instrumentation with respect to these grounds. So, one thing which, I think, is very very necessary for any following up on this in the line of measurements, or on the line of installations, is that there should be some kind of a measurement of the resistivity of the soil around the installation. This is necessary so that we can know something about the relaxation time of this soil to distribute the charge which has been spread over several kilometers and has to be collected rapidly at a point. It we don't know these things and if there is no way to get that charge together fast, you are going to get a lot of crazy results and we will never know what's happening.

Hans Dolezalek

I think George Freier is very right. Let me make a very simple statement, which for an atmospheric electrician is obvious, but maybe not for all people. What we really mean with the term "ground" is the resistance between that

point which we call ground, and the world's oceans. That is so because every current has to be in a closed loop. In the case of lightning, that is the loop which constitutes part of the atmospheric electrical circuit. A few months ago I had experienced a heavy thunderstorm in a house in Vermont. I was sitting in the basement where there were a lot of sparks, one from each of the many lightnings in the neighborhood. The ground which was provided in this house (and had been very well made by the electricians) went to the well from which the house got its water. That ground obviously was not as good as a certain other ground, namely the ground to the septic tank with which the house was also installed. For some reason the lightning always wanted to go to the septic tank and not to the well. A second point: This is a condition which often cannot be predicted - obviously the resistance from the septic tank to the oceans was less than that from the well. I have the feeling we did not discuss sufficiently one realistic topic which was brought up by Rodney Bent. That topic may already give us some insight into the problems we are discussing here. It is the great discrepancy (by three orders of magnitude) in the corona currents measured. Obviously, what Rodney Bent was calling the "ground current" was what also has been called the Telluric Current. He seems to think that this Telluric Current can be so high and can go somehow into the equipment and cause the high currents which were reported in some of the government reports. This deserves more attention, I believe.

J. Hughes

It occurs to the chair that after that strike to the septic tank, it must have been an aseptic tank.

Dr. Heinz Kasemir

I am coming back to the experiment and the theory. I think if you try to understand it, which I would like to do, we will still be here after a couple of years discussing things. If I focus again on this one question, does the array work or doesn't it work, I think the experiment is not so difficult to set up. We have to have null hypothesis for the statistician which is very easy. No difference between the lightning strikes to the tower which has the array and the control tower. And here for the statistician you always have to have a controlled experiment, the not treated tower and the treated tower. So there is a very simple statistical evaluation, even if you have only ten or fifteen lightning hits per year to say with such and such significance, and with such and such a power of the test, this is not the result, this is the difference. Using KSC as the place to set up this thing where you have not only the weather report, but you have the field mill report sometimes. I think they will mothball the field mills, but they may put them out again during the summer time next year. You have the towers, not only one but a lot of towers standing out there. It shouldn't be too difficult to take one tower, it doesn't have to be 1500 ft. high. A lower tower will do just as well. There is really not too much difference to set up an instrument or an experiment which satisfy the statisticians. The difficulty is a little bit more in keeping up the equipment and doing it right from the beginning and giving Mr. Carpenter all the time to make as good an array as he can with whatever grounding he wants. After we start the experiment there should be no touching and no rewiring or rebuilding. I would suggest that we really seriously concentrate on this one point, seeing if we can experimentally decide the working of this equipment.

Dr. Rodney Bent

Two points here. Firstly, let me answer Hans Dolezalek's question about what I meant by ground current. What I meant here was that if I stick two rods in the ground at different points, join them with a wire and a meter a current will flow. I believe this is the Telluric Current. If the array has a resistance to the tower, which it had in the case that I mentioned, the array has a wire taking it to ground through the measuring equipment. The tower goes to another ground. This is a situation where we have current measurements of the order of 100 to 150 microamps, which I thought may have influenced the measurements of the corona dissipation. Secondly, I hear Dr. Kasemir again mentioning that he would like to investigate to see if the array works. Dr. Few has already answered this point negatively and very well. Mr. Carpenter mentioned that the 11 strokes we had monitored to the Eglin Tower were because that tower was not properly protected. I had also briefly mentioned a Central Florida Facility and we have not heard from Mr. Carpenter that the arrays on the car park are badly installed. We must, therefore, assume they were installed correctly. We have many video pictures of cloud to ground lightning going straight down to this large facility. Many of these were in the area of the car park. We have not yet plotted the strike points, but we are going to draw maps of the movements of these storms. It appears that the results from this site will probably be very similar to what we saw at Eglin. Namely, that the "protected" area is not protected by the arrays. Therefore, why put more money into investigating it, and repeating the experiments at KSC that have already been done at KSC and elsewhere with arrays on tall towers and at the same height as single points. Let's see more money put into Dr. Moore's research to look at the blunt points and single point dilemma.

Roy Carpenter

I take exception to the comments that the Disney World area has been struck by lightning. I just talked with the gentlemen who is in charge of that program just before I came in. His position and his comments were that they have not been struck. They have no record of any damage in that area whatsoever. And I asked him that specific question just before I came here.

Dr. Rodney Bent

Yes, he also asked me the other day when he was going to get our report. This report, on the lightning activity at a Central Florida entertainment location has not yet been published. But, we do have many strikes to ground recorded in this dissipation array region.

Roy Carpenter

I am not sure I understand, would you repeat.

Dr. Rodney Bent

We are the ones that analyzed the video tapes, the company staff did not. We have photographs of the strikes and they will be fully published showing the precise points where the discharges occurred.

Dr. Heinz Kasemir

You say the strikes to ground. Do you mean to the array?

Dr. Rodney Bent

No, to the area. We don't know if they hit an array or not. The car park is an enormous area with many of these arrays, which according to what we heard today, are supposed to protect the car park area. They do not protect the lamp posts that they are on, they are supposed to protect the whole car park area.

Roy Carpenter

We have in the Disney World complex just two array systems that are in operation, and there are just two areas that are presently being protected. One is what they call the main parking lot, the other is Space Mountain. And again just as recent as three or four days ago I was in communication with the person who is responsible for the arrays and he said they have had no strikes and no damage in either place.

Dr. Barreto

Have you ever taken one of these arrays put it in a gap, which is much bigger than the separation between points, and connect it to an oscilliscope to see what the discharges look like? I don't think there is any other way to determine if the coronas go point by point and it makes absolutely no difference if you have either a lot of points or one point.

Roy Carpenter

No. We have not made such a measurement.

Dr. L. Ruhnke

There is one point to consider with grounding. It is very important for lightning when it strikes that it is properly grounded. But for the array to work properly, you don't need as much care in the grounding. Assume you have a one mega ohm resistance between the array and ground, then with about 100 microamps you would lose 100 volts. With high electric fields and with the high position of your array, that does not affect your corona current in any way. So grounding should be no problem for the array.

Roy Carpenter

You are correct. The grounding system is much less sophisticated for our system than it is for a conventional system that is attracting lightning. We are less concerned about the grounding resistance than we are with ground contact. We are trying to collect a charge and couple it to an array through a preferred path.

Dr. Lothar Ruhnke

Since this is about the end, I would like to give my assessment of the situation this afternoon. Experimental evidence that arrays eliminate or divert lightning is insufficient. No theoretical evidence suggest that arrays eliminate or divert lightning to a significant degree. The problem of protecting large structures against lightning still exists, it is a real problem. The problem is of considerable complexity if improvements against present day state-of-the-art lightning rods and grounding methods are concerned. And the last point I would like to make is that scientists are urged to direct attention to this complex problem and suggest a proper course of action.

J. Hughes

We have seemed to have temporarily exhausted the subject. We have tried to make the assessment and when we publish our report we'll have to give the observations such as they are, and let people make their interpretation then. We won't give any strong opinions on them, but we will give the observations. We've attacked a narrow part of the lightning problem, as you all understand. There is beyond that the problem of lightning warning. The attempt to predict, or forecast when lightning in an area will arrive over a spot so that we have enough time to take precautions. But no matter how good our predictions are, if the lightning arrives and we know it is going to arrive, we still have the problem of protection, so there is no way of avoiding that problem. I don't know what progress we can make beyond this point in the design of an experiment. The one thing apparent from the meeting is that there is skepticism that we have an effective means of preventing lightning, but this is not the end of the story. We still have to get some criteria, maybe some more effective experiment. Those of you who are interested in designing that experiment, you have an open invitation from Kennedy Space Center to make the attempt. I thank you all for coming. Each of the attendees on the list will get a copy of the report eventually. Each of you who made a presentation, I hope you will give us your text and any illustrations you wish to include.